Middlesex University London

School of Science and Technology

I100 - PhD in Computer Science

Investigation and Development of a Tangible Technology Framework for Highly Complex and Abstract Concepts

Date	June 2018
Student Name	Clifford De Raffaele
Student ID Number	M00490574
Director of Studies	Serengul Smith
Supervisor	Orhan Gemikonakli
Campus	Middlesex University, London

A thesis submitted in partial fulfilment of the requirements for the degree of Doctorate of Philosophy in Computer Science

Ph.D. Advisory Committee

Prof. Paul Gibbs (Chair)

Prof. Liz Bacon (External Examiner)

Dr Robert Laramee (External Examiner)

Abstract

The ubiquitous integration of computer-supported learning tools within the educational domain has led educators to continuously seek effective technological platforms for teaching and learning. Overcoming the inherent limitations of traditional educational approaches, interactive and tangible computing platforms have consequently garnered increased interest in the pursuit of embedding active learning pedagogies within curricula. However, whilst Tangible User Interface (TUI) systems have been successfully developed to edutain children in various research contexts, TUI architectures have seen limited deployment towards more advanced educational pursuits.

Thus, in contrast to current domain research, this study investigates the effectiveness and suitability of adopting TUI systems for enhancing the learning experience of abstract and complex computational science and technology-based concepts within higher educational institutions (HEI)s. Based on the proposal of a contextually apt TUI architecture, the research describes the design and development of eight distinct TUI frameworks embodying innovate interactive paradigms through tabletop peripherals, graphical design factors, and active tangible manipulatives. These computationally coupled design elements are evaluated through summative and formative experimental methodologies for their ability to aid in the effective teaching and learning of diverse threshold concepts experienced in computational science.

In addition, through the design and adoption of a technology acceptance model for educational technology (TAM4Edu), the suitability of TUI frameworks in HEI education is empirically evaluated across a myriad of determinants for modelling students' behavioural intention. In light of the statistically significant results obtained in both academic knowledge gain (μ = 25.8%) and student satisfaction (μ = 12.7%), the study outlines the affordances provided through TUI design for various constituents of active learning theories and modalities. Thus, based on an empirical and pedagogical analyses, a set of design guidelines is defined within this research to direct the effective development of TUI design elements for teaching and learning abstract threshold concepts in HEI adaptations.

Acknowledgements

The accomplishment of this study could not have been possible without the assistance and participation of numerous entities whose names may not all be enumerated. With boundless appreciation, I would like to express my sincere gratefulness to all those who helped in making this research possible.

In particular, I owe the success of this research to my mentoring team and academic colleagues, Prof. Serengul Smith and Prof. Orhan Gemikonakli. I have never ceased to admire these two extremely dedicated and talented academics, who showed unwavering belief in my abilities and brought out the best of me in both academia and personal development. They have continuously challenged, instructed, and constructively guided me throughout all stages of this journey and incessantly provided invaluable opportunities to develop myself in both academic and professional aspects.

I would also like to express my profound appreciation to all my academic colleagues at Middlesex University Malta, who have been essential in providing me with a stimulating environment to work in. I am grateful for their assistance, encouragement and for all the insightful discussions which have helped me improve my work. I would also like to deeply thank all the students who have contributed towards the deployment and evaluation of this research, collectively they were instrumental for developing and assessing the proposed ideas and contributions of this study.

Heartfelt thanks go to my closest family with whom I shared the achievements and struggles of this study and who relentlessly were a continuous source of encouragement and emotional support to help me through. Above all, I am forever indebted to my parents who have always sought to make it possible for me to continue learning and further improve my knowledge whilst helping me grow to the man I am today.

Finally, I would like to dedicate this work to my girlfriend Maxine for her infinite patience, support and love during this journey, without her, this life milestone would have definitely not been possible.

Dissertation Structure

This section provides an outline of the entire dissertation structure as to provide context of the work done, together with understanding of the descriptive flow in which the research contributions will be described.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Notations

1NF	First Normal Form
2D	Two-dimensional
2NF	Second Normal Form
3D	Three-dimensional
3NF	Third Normal Form
AI	Artificial Intelligence
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
API	Application Program Interface
AR	Augmented Reality
ARCS	Attention, Relevance, Confidence and Satisfaction
ASC	Autistic Spectrum Condition
BI	Behavioural Intention
CA	Computer Anxiety
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CPU	Central Processing Unit
CSE	Computer Self-Efficacy
CSV	Comma-Seperated-Value
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name Server
ERD	Entity Relationship Diagram
GUI	Graphical User Interface

HCI	Human-Computer Interaction
HEI	Higher Educational Institute
HRI	Human Robotic Interactions
I/O	Input / Output
ICT	Information Communication Technology
ID	Identifier
IDE	Integrated Development Environment
IoT	Internet of Things
IP	Internet Protocol
IR	Infra-Red
IS	Information Systems
IT	Information Technology
KMO	Kaiser-Meyer-Olkin
LAN	Local Area Network
LED	Light Emitting Diode
MANOVA	Multivariate Analysis of Variance
MAR	Missing at Random
MCQ	Multiple Choice Questionnaire
MCRpd	Model-Control-Representation (Physical and Digital)
MLA	Machine Learning Algorithm
MOOC	Massive Open Online Courses
MRA	Multivariate Regression Analysis
MVC	Model-View-Controller
NFC	Near Field Communication

OOP	Object-Oriented Programming
OSPF	Open Shortest Path First
PC	Personal Computer
PENJ	Perceived Enjoyment
PEU	Perceived Ease of Use
PFL	Pedagogical Framework Learning
PLA	Perceived Lecture Attention
PLA	Polylactide
PU	Perceived Usefulness
PVC	Polyvinyl chloride
RBI	Reality-Based Interaction
RFID	Radio Frequency Identification
RGB	Red – Green – Blue
ROS	Robot Operating System
SE	Self-Efficacy
SOCINT	Social Interactivity
SPSS	Statistical Package for Social Sciences
STEM	Science, Technology, Engineering and Mathematics
STREL	Study Relevance
SWOT	Strengths, Weaknesses, Opportunities and Threats
TAC	Token and Constraint
TAM	Technology Acceptance Model
TAM2	Technology Acceptance Model 2
TAM4Edu	Technology Acceptance Model for Education

TANX	Technology Anxiety
TPB	Theory of Planned Behaviour
TRA	Theory of Reasoned Action
TUI	Tangible User Interface
UAT	User Acceptability Testing
USE	Usability
URP	Urban Resource Planner
VARK	Visual, Aural, Read/Write and Kinesthetic
WIMP	Windows, Icons, Menus, Pointers
WLAN	Wireless Local Area Network
WWW	World Wide Web
XML	Extensible Markup Language

Glossary of Terminology

Architecture	Within the scope of TUI research, nominally in chapter 4, TUI architecture refers to the system configuration and integration of hardware devices within the form-factor of the technology. A TUI tabletop architecture is adopted within this study composed of an interactive surface whereby digital data projection and video capture is undertaken to track interactive objects. This conventional architectural design is extended further by the contributions of this study within HEI.
Computational Science and Technology Subjects	The domain investigated throughout the study is predominantly scoped towards courses and programmes at undergraduate and postgraduate level. The term encompasses a subset of high-level domains including; computer science, information systems, computer networks, data science and technology engineering which are evaluated throughout this research.
Framework	The term is predominantly employed throughout the study to refer to TUI Frameworks which are designed and developed in chapter 5. Within the context of this research, a TUI Framework encompasses the design and integration of different TUI elements including; hardware architecture, tangible manipulatives, data communication protocols and graphical software development. Within chapter 6, the term framework is also utilised to describe the validated design of a Technology Acceptance Model (TAM). Thus, TAM framework comprehensively entails a set of constructor determinants, an evaluation questionnaire, and a validated set of hypotheses explaining user behavioural intention towards technology.

Participants	Participants engaged within the undertaking and evaluation of this research where all recruited on a voluntary basis. Evaluating users were composed of undergraduate and postgraduate students enrolled within the faculty of science and technology at the Middlesex University Malta campus. The study also undertook the participation of academic experts and members of staff within the Malta and London campuses of Middlesex University, who's domain of expertise and research interest coincided directly with the educational subjects considered.
Tangible User Interface	As a distinct technology placed within the reality-based interaction domain, tangible user interfaces (TUI) are computationally mediated systems that differ from Augmented Reality (AR) and Virtual Reality (VR) by computationally and perceptually coupling physical manipulation as a means of interaction with digital information. Unless explicitly referred to otherwise, within the context of this dissertation TUI refers to a tabletop system
Threshold Concepts	Adopted from educational pedagogy literature, threshold concepts refer to a subset of knowledge concepts which constitute a core and abstract concept within curricula and are commonly difficult to teach and learn. As detailed in section 7.2, these concepts are generally defined by characteristics including; transformative, irreversible, integrative, bounded and troublesome knowledge. Within the context of this research, the difficulties encountered in teaching and learning threshold concepts form the foundational scope for design and development of TUI frameworks in higher education.

Chapter 1 Introduction

1.1 Motivation

The inspiration for this study, stems from the academic and personal experiences obtained though lecturing science and technology modules within higher educational institutes (HEI)s. Primarily motivated by the several difficulties encountered when delivering abstract and complex concepts within university programmes, this research investigates the suitability of educational technology to aid in the teaching and learning of such threshold concepts. Through a computer science insight, this study analyzes the harboured capabilities of interactive technology to represent and engage conceptual representations in educational contexts. Thus, motivated by the potential design capacity of tangible technology to suit pedagogical approaches and technical affordances, this study progressively investigated the design and development of various Tangible User Interface (TUI) frameworks to effectively engage HEI students. Encouraged by exploratory results, the study addressed a research niche within the field of TUI literature by considering the educational design of tangible interaction for teaching and learning abstracted notions, within higher educational contexts. This motivation led to the development and formalisation of this study through research and empirical validation as detailed in this dissertation.

1.2 Theoretical Background

1.2.1 Traditional Lecturing as a Problem

Albeit the evolution and use of modern technology has brought about drastic advancements in a myriad of applications within the educational sector, traditional lecturing[1] still dominates as the de facto practice across disciplines (Mazer and Hess, 2017). Whilst evidently able to simultaneously address large-group communication in a resource-efficient manner (Lambach, Kärger and Goerres, 2017), this traditional methodology also provides lecturers the ability to comfortably determine the organisation, pace, direction, and content of a particular session, thus enabling the educator to directly control subject teaching (Hernández-López *et al.*, 2016).

Concerns about the adequateness of traditional lectures, in light of the one-way passive format along which they are usually undertaken, have however stemmed over the years from both anecdotal impressions as well as research data (Severiens, Meeuwisse and Born, 2015). Numerous studies have repeatedly observed drawbacks such as low scores during exams, decreased class attendance rate and an overall negative perception towards the education process (Maloney and Lally, 1998). This can be explained in part, by the fact that traditional lecturing follows a single learning pace and hence does not cater for the difference in learning practices by students (Kharb *et al.*, 2013). Additionally, with the rapid proliferation of distractors, such as smartphones and wearable devices, maintaining full concentration during a lengthy traditional lecture, is becoming evermore challenging for students (Tindell and Bohlander, 2012).

[1] A ‘traditional lecture’ is defined by the continuous exposition of material by the teacher, with students passively listening and receiving knowledge in a lecturer-centred pedagogy. Consolidation and application of knowledge take place in the individual follow-up phase which is possibly augmented by assignments.

1.2.2 Active Learning as a Solution

In a bid to address the shortcomings associated with traditional lectures, educators have striven to alter the way in which teaching and learning are conducted (Price and Rogers, 2004). Prominent amongst alternatives to traditional lecturing ideologies, is the sustained interest garnered for active learning, which aims at integrating the student further with the educational process (Felder *et al.*, 2000; Prince, 2004). Central to active learning is the direct engagement of students with the learning paradigm, whereby the latter are actively or experientially involved through the entire process (Weltman, 2007). This is attained by adopting a pedagogical approach in which students are expected to read, write, collaboratively discuss with peers, and to be directly engaged with problem-solving tasks (Terenzini *et al.*, 2001).

As a result of being more student-centred, active learning has been associated with a significant change in student behaviour towards sessions, a more positive perception of the learning process and consequently a catalyst for higher exam scores distributions when compared to traditional lectures (Blasco-Arcas *et al.*, 2013; Mellecker, Witherspoon and Watterson, 2013; Freeman *et al.*, 2014).

1.2.3 Technology as an Opportunity

Underpinned by this appeal, computer-based technology has emanated as the preeminent approach for enabling the enhancement of active teaching and learning (Nasman and Cutler, 2013), with the development and implementation of educational technologies experiencing a persistent growth in the past decade (Dabbagh *et al.*, 2016). As technology further morphed the transformation of computer systems into interconnected portable and personal devices, academics and students alike were able to explore the vast abilities of this technology to provide enriched and diverse information to aid in their perusal (Williams, 2002).

Yet, whilst instant access to a plethora of open educational resources has nowadays become prevalent within classroom environments, it is commonly agreed that merely providing access and availability to such knowledge through technology is not an effective way to stimulate teaching and learning (Bush, Terry and Languages, 1997). This consequently led to a shift in the educational paradigm whereby educators are no longer sought to deliver knowledge and data content (Jones and Sallis, 2013), but rather required to elicit students the necessary skills to engage with the available data and further their understanding in a dynamic manner (Sun *et al.*, 2015). Thus, effective teaching and learning within a technological context is evolving as being more of a process-driven approach, than the knowledge transfer technique that it traditionally was (Vu, Abel and Morizet-Mahoudeaux, 2015).

Similar admonitions have also been highlighted, with respect to the deployment of educational software packages and social media platforms which are becoming increasingly ingrained within curricula (Price and Rogers, 2004). As the latter is continuously targeting the proliferation and popularisation of personal devices amongst students, the inherent nature of these user-centric platforms has constrained the effectiveness of educational technology to deliver on some critical interactive and collaborative aspects central to active learning (Rambe and Nel, 2015). Consequently, ICT implementation in classrooms tends to support more passive forms of learning, with most software often under-delivering in the educational value expected by their multimedia capabilities (Laurillard, 2013).

Thus, this led stakeholders to appreciate the fact that the emergence of technology as a suitable solution for education, entails not only the availability of resources, but also a well-designed study plan for proper integration and exploitation of the resulting technological advantages (Takahashi *et al.*, 2016). The inherent ability of educational technology to engage students in their learning environment, presents a repertoire of options which allows for a more interactive involvement with the learning process (Mellecker, Witherspoon and Watterson, 2013). Rather than being a platform for educational provision, different technologies can be combined to influence the educational experience of students, enabling the customisation of learning that could be collaboratively explored.

These benefits have been sought after with varying success in primary education, whereby student engagement and interest are given particular attention (Abdul Razak and Connolly, 2013). Adopting these educational tools in higher education, however, brings along a number of interesting possibilities. Catering to a more mature audience provides the ability for technology to promote the self-driving aspect of teaching and learning. This is carried out whilst capitalising directly on experimental approaches and innovative solutions devised by the students themselves. To this end, research in the literature has consistently asked for the development of new paradigms within which students are able to interact and visualise information through learning experiences which promote and facilitate the ability to self-engage with their learning content (Schneider and Blikstein, 2016).

1.2.4 Tangible User Interfaces as an Alternative

The limitations and constraints of conventional personal computer (PC) setups have led to the development and investigation of alternative technological platforms for user interactivity, whereby Tangible User Interfaces (TUI) steadily emerged and, in the past years, garnered interest within both academia and industry alike (Shaer & Hornecker 2010). Capitalising on the natural familiarity of physical movements, bodily posture changes and object manipulation within the physical world (Ishii and Ullmer, 1997), TUI systems challenge the isolating boundary between physical interaction and digital representation and closely interlink these domains together. As opposed to conventional Graphical User Interfaces (GUI) systems, TUI's implementations go beyond the limited use of conventional computer peripherals (such as keyboards and mice) and permit users to interact with digital information through the manipulation of physical objects (Wagner, Nusbaum and Goldin-Meadow, 2004; Garber, 2012). This enables users of TUI systems to take advantage of innate spatial and environmental skills (Ishii, 2008a), whilst interacting with and configuring physical objects (Rodríguez Corral *et al.*, 2014). Both these interactive attributes have been correlated with the enhancement of problem-solving skills (Schneider *et al.*, 2011), as well as an inherent heightened sense of user engagement. Thus, this led TUI developments to be positively correlated with the ability to augment higher-order cognitive activities in users such as, attention, inquisitiveness, reflection, thinking and reasoning (Price and Rogers, 2004).

The highlighted benefits of this technology, together with its inherent attractive engagement aspect, has led to TUI systems quickly gaining exposure within primary and kindergarten schools (Antle, 2007; Tanhua-Piiroinen, Pystynen and Raisamo, 2010; Maquil and Ras, 2012; Ras *et al.*, 2014; Cuendet *et al.*, 2015). Numerous studies have further investigating TUI effectiveness in educating young children, reporting benefits in captivating student attention through attractive, fun and visually-striking interaction (Yonemoto, Yotsumoto and Taniguchi, 2006; Shaer and Hornecker, 2009; Farr, Yuill and Raffle, 2010; Devi and Deb, 2017). Furthermore, the ability to provide physically engaging collaborative activities, allows tangible interfaces to facilitate child interaction through the conventionally “boring” educational phases of story and music compositions (Tanenbaum and Tomizu, 2008; Waranusast, Bang-ngoen and Thipakorn, 2013).

The success registered in current research on child-based educative TUI systems, however, chiefly aims to intrigue and entertain students whilst in consequence exposing educational concepts (Price *et al.*, 2003; Nusen and Sipitakiat, 2012; Agrawal and Sorathia, 2013; Bumbacher *et al.*, 2013). Unfortunately, this design methodology has led TUI frameworks in failing to scale with equal effectiveness when utilized with adult higher-education users

(Stanton *et al.*, 2001; Sluis *et al.*, 2004; Ullmer, Ishii and Jacob, 2005; Schweikardt *et al.*, 2009; Schneider and Blikstein, 2015).

The exploitation of TUI learning capabilities for more elaborate and abstract concepts has in contrast been quite limited, with more complex adaptations seen mainly within the industrial settings (Edge and Blackwell, 2006). TUI developments within the architectural domain were thus employed to model the illumination, wind and shadow casting effects of multiple buildings during different daylight stages (Underkoffler and Ishii, 1999; Nasman and Cutler, 2013). The ability to visualise and model physical systems, also proved to be useful in various industrial applications providing the enhanced capacity for terrain design in storm water runoff management and airspace modelling for air traffic controllers (Mackay and Fayard, 1999; Tateosian *et al.*, 2010). Commercially, the ability to interactively simulate complex scenarios has been adopted for enterprise network infrastructure management, whereby clients can visualise traffic flow and identify network bottlenecks for various architectural options (Kobayashi *et al.*, 2003a, 2006; Narita, 2004).

1.3 Research Scope

1.3.1 Research Question

The contribution of this study lies at the confluence of the outlined literature, and thus this research aims to investigate the question;

Are tangible user interfaces an effective and suitable technology to explain abstract and complex concepts in higher education?

To this extent, in line with the research categorisation defined by Hendrick et al (1993), a set of subordinate research questions will be explored within this study as enlisted hereunder.

- **Descriptive:** What are the benefits of TUI systems in education?
- **Normative**: Are TUI tabletop architectures suitable for use in higher educational institutes?
- **Impact**: What are the effective interactive methods that can be employed in TUI frameworks to aid in the teaching and learning of threshold concepts within computational science and technology subjects?
- **Correlative:** What factors influence the acceptance of TUI systems in higher education?
- **Correlative:** How does the design of tangible elements aid in the teaching and learning pedagogy of abstract and complex concepts?

1.3.2 Dissertation Overview

Throughout this research, a comprehensive literature review has progressively been conducted on articles to date within the field of Tangible User Interfaces (TUIs), in order to holistically understand current works on the technology and its implementation instances. As critically detailed in the literature taxonomy within chapter 2, this study identified a research niche within the development and design of TUI systems for educational uses in HEI contexts.

Thus, in contrast to current research within the domain of TUI, this study investigates the capabilities of TUI systems to aid in teaching, and learning, highly complex and abstract concepts in HEIs. Converse to the needs of primary and secondary education, and based on a literature overview of TUI developments, the proposal of a TUI architecture design that explicitly addresses the differential requirements of the studied area, is described within chapter 4.

The study distinguishes itself by proposing a series of TUI framework designs in chapter 5, that directly aim to provide a tangible visualisation and interaction paradigm for the educational pursuit of teaching and learning abstract and complex concepts. These TUI frameworks empirically outline the capacity of tangible technology design to ingrain active learning pedagogies and provide participants with the opportunity to collaboratively investigate and informatively interpret abstract concepts through tangible interaction. As a result, chapter 6 provides an empirical study in which TUI frameworks are purposely designed to interactively expose HEI students to practical elements of computational science and technology concepts, whilst at the same time pedagogically assisting in their cognitive understanding of abstracted notions. From a computer science perspective, the proposed TUI design architecture has been extended through the integration of several interactive design elements, including actively embedded tangibles, graphical design factors and interactive peripherals. These tangible designs were appropriately contextualised in various domains, ranging from computer networks to databases, robotics, and artificial intelligence, so as to objectively assess the effectiveness of TUI frameworks in teaching and learning diverse computational science and technology-based threshold concepts.

In a strive to evaluate the suitability of TUI systems for educational use within an HEIs, this research has further analysed the manner in which novel technology acceptance is being evaluated and modelled. In line with available literature on Technology Acceptance Models (TAM) in the industry, chapter 6 analyses the applicability of various adopted models and determinant metrics in educational contexts. Based on an empirical evaluation analysis of models' determinant, this study evaluates and proposes a TAM framework adoption for the unique attributes and requirements of educational technology in HEI contexts. Within chapter 6, this acceptance model is subsequently statistically validated and employed to assess the technological suitability of adopting TUI frameworks in direct comparison to the current educational technology used in the domain.

A pedagogical reflection on the adequacy of the TUI frameworks designed within this research is further undertaken in chapter 7, whereby the aptness and effectiveness of TUI systems to combine different learning modalities and strategies is theoretically evaluated. A reflective evaluation is further undertaken in this chapter to derive a set of descriptors for the various threshold concepts identified within higher education in computational science and technology-based subjects. Thus, based on this analysis, chapter 7 proposes a set of empirically and pedagogically evaluated TUI design guidelines for the development of educational tangible frameworks to effectively aid in the learning of abstract and complex concepts.

In conclusion, chapter 7 provides a synoptic review of the obtained evaluation results which underpin a reflective analysis on the various strengths, weakness, opportunities, and threats (SWOT) experienced when adopting TUI as an educational technology. The limiting factors outlined in TUI adoption are further detailed within this chapter, identifying avenues for further research within the field.

1.4 Research Contributions

This research studies the unexplored domain of adapting tangible user interfaces for effective implementation to teach and learn the highly complex and abstract domains commonly encountered in higher education. To this end, the study contributes to scientific knowledge by introducing:

- ***Educational TUI framework designs for HEI contexts.***

  A number of contributions have been undertaken in diverse computational science and technology domains by designing, implementing, and extending the tangible interactive paradigm of TUI frameworks for teaching and learning respective threshold concepts. The design capabilities of the proposed TUI designs is experimentally validated on its effectiveness to aid the delivery of abstract and complex notions within university programmes.

In pursuit of this contribution, this research undertook convergent work which contributes further to the scientific domain by providing:

- ***A taxonomy on TUI architectures in the educational domain.***

  A comprehensive and structured literature review is developed on the adaptions of tangible user interface architectures within education. This critical review assessment presents the beneficial and limiting factors of TUI developments, outlining areas of research that still require investigation.

- ***A TUI interactive tabletop architecture to support HEI contexts.***

  The physical limitations outlined in the literature on TUI architectures, have been formally compiled and addressed by the proposal of an adapted TUI design for teaching and learning in HEI. This deliverable describes the design and development considerations for an effective TUI architecture to mitigate the requirements pertaining to this domain.

- ***A Technology Acceptance Model for Education Technology.***

  Founded on an analysis of literature models for evaluating technological acceptance, the study empirically reflects on the applicability of these metrics in educational contexts, and consequently proposes and validates a dedicated technology acceptance model for educational technology (TAM4Edu).

- ***TUI Design Guidelines for Abstract Concepts.***

  Based on threshold descriptors of abstract and complex computational science and technology-based concepts, the study introduces a set of TUI design guidelines. These tangible design considerations are pedagogically and empirically evaluated to guide the technology design elements for the effective development of TUI frameworks to teach and learn threshold concepts.

1.4.1 Supporting Publications

During the course of this PhD study, the following international peer-reviewed academic papers were derived and published to date, in support of the scientific contributions to knowledge developed within this research:

- De Raffaele, C., Smith, S. and Gemikonakli, O. (2015) 'A Tangible Technology Framework for Visualising Highly Abstract Concepts', in Middlesex University Research Student Summer Conference (RSSC 2015). Hendon, UK – **Awarded Best Poster Presentation**.

- De Raffaele, C., Smith, S. and Gemikonakli, O. (2016) 'The aptness of Tangible User Interfaces for explaining abstract computer network principles', in *Proceedings 46th IEEE Frontiers in Education Conference, (FIE 2016)*. Eire, Pennsylvania, pp. 1–8.

- De Raffaele, C., Smith, S. and Gemikonakli, O. (2016) 'Teaching and Learning Queueing Theory Concepts using Tangible User Interfaces', in

Proceedings of 2016 IEEE International Conference on Teaching, Assessment and Learning for Engineering, (TALE 2016). Bangkok, Thailand: IEEE, pp. 194–201. **– Awarded Best Paper**.

- De Raffaele, C., Smith, S. and Gemikonakli, O. (2017) 'The Application of Tangible User Interfaces for Teaching and Learning in Higher Education', in Branch, J. (ed.) *Innovative Teaching and Learning in Higher Education*. Copenhagen, Denmark: Libri Publishing, pp. 215–226.
- De Raffaele, C., Buhagiar, G., Smith, S. and Gemikonakli, O. (2017) 'Designing a Table-Top Tangible User Interface System for Higher Education', in *IEEE International Conference on Smart Systems and Technologies (SST 2017)*. Osijek, Croatia: IEEE, pp. 286–291.
- De Raffaele, C., Smith, S. and Gemikonakli, O. (2017) 'Enabling the Effective Teaching and Learning of Advanced Robotics in Higher Education using an Active TUI Framework', in *ACM AME Conference on Software Engineering (AMECSE 2017)*. Cairo, Egypt: ACM, pp. 1–6.
- De Raffaele, C., Smith, S. and Gemikonakli, O. (2017) 'Explaining multi-threaded task scheduling using tangible user interfaces in higher educational contexts', in *IEEE Global Engineering Education Conference (EDUCON 2017)*. Athens, Greece: IEEE, pp. 1383–1390. **– Awarded Outstanding Paper**.
- De Raffaele, C., Smith, S. and Gemikonakli, O. (2018) 'An Active Tangible User Interface Framework for Teaching and Learning Artificial Intelligence', in *Proceedings of the 23rd International Conference on Intelligent User Interfaces (IUI 2018)*. Tokyo, Japan: ACM, pp. 535–546.
- De Raffaele, C., Borg, M., Smith, S. and Gemikonakli, O. (2018) 'A Tangible Approach to Teaching and Learning Search-Space Concepts in Higher Education', in *IEEE Transactions on Education* - under review.

Chapter 2
A Taxonomy of Tangible User Interfaces

2.1 Tangible User Interfaces

The term Tangible User interface (TUI) as coined by Ishii and Ullmer (1997), describes a computing technology which uses physical objects as inputs and for interaction with the digital information. Extending the concepts in Graphical User Interfaces (GUI), TUI systems "*couple physical representations (e.g., spatially manipulable physical objects) with digital representations (e.g., graphics and audio), yielding interactive systems that are computationally mediated, but generally not identifiable as 'computers' per se*." (Ullmer and Ishii, 2001). This technology, thus, proposes a hidden modern approach to ubiquitous computing by combining the digital technology and the physical environment (Ishii, 2008b; Redström, 2008), consequently introducing a computing approach within everyday life which reacts to real life situations (Terrenghi *et al.*, 2006; Eom *et al.*, 2008). This aligns with Weiser's (1993) vision of ubiquitous computing where the digital world will blend into the physical world seamlessly and technology moves with us effortlessly (C. O'Malley and Fraser, 2004).

TUI systems conceptualise this technology *'invisibility'* by interweaving the digital and physical worlds through embedding computation in physical artefacts and environments (Shaer, Horn and Jacob, 2009). Physical TUI objects are thus linked to the digital information within TUI architectures, and this allows users to mutually interact with the digital information by manipulation in a real-world environment (Patten, Griffith and Ishii, 2000; Schneider *et al.*, 2011). Incorporating a mixture of general-purpose (time-multiplexed) and specific-function (space-multiplexed) objects (Fitzmaurice, Ishii and Buxton, 1995), TUI architectures are able to embed a combination of interactive mappings (Mazalek and van den Hoven, 2009). Augmentation of real-world objects is attained by instilling in them '*digital meaning*' whilst also adding a manipulation dimension to the object itself (Jacob *et al.*, 2002). Thus, whilst these objects are manipulated by natural gestures such as moving, shaking and turning, TUI systems utilise the data received to alter the digital information accordingly, thus generating a *'smart object'* user experience (Fishkin, 2004; Sharlin *et al.*, 2004; Ishii, 2006; Zappi *et al.*, 2009). These interactive mappings can be classified as either behavioural mappings, which refer to the output results from user inputs on a TUI system, or, semantic mappings, that indicate the information communication between the digital and physical aspects (Antle, 2007). Hence, TUI objects provide a model and control for the actual space they take up, having them mapping the virtual space being used (Antle, 2007).

2.1.1 Interaction Models

Extending on the model-view-controller (MVC) structure used for GUI, depicted in Figure 2.1(a) (Krasner and Pope, 1988), Ullmer and Ishii (2001) formalised an interaction model for TUI architectures by proposing the model-control-representation (physical and digital) (MCRpd) shown in Figure 2.1(b). Unlike the MVC model, which considers conventional input/output devices and assumes that all system computations are undertaken electronically, the MCRpd model outlines the TUI manipulation capacity within the physical control and representation relations (Koleva *et al.*, 2003).

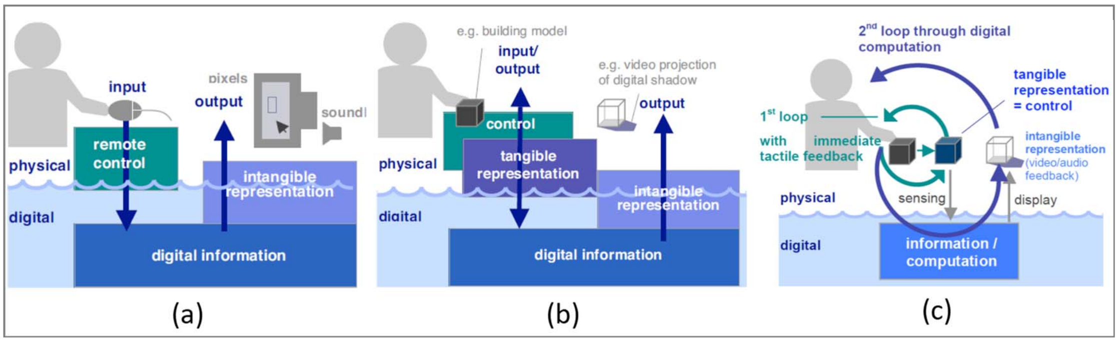


Figure 2.1: Interaction Control Models:
a) MVC model for GUI architectures (Krasner and Pope, 1988)
b) MCRpd model for TUI architectures (Ullmer and Ishii, 2001)
c)TUI double feedback loop through tactile and digital feedback (Ishii, 2008a).

Ullmer and Ishii (2001) utilised the model in Figure 2.1(b) to describe the four characteristics by which TUI architectures combine the physical system within spatial, relational or constructive interpretations (Antle, 2007). The first characteristic within this model, outlines the computational coupling between physical representations and their underlying digital information (*model*), whilst the second characteristic, highlights the embodiment of physical representations with interactive control mechanisms (*control*). The third characteristic emphasises the perceptual coupling of feedback returned to a user on physical representations via actively mediated digital representations (*representation digital*). The last characteristic outlines the persistent nature of TUI objects and thus the embodiment of the system's digital state within the physical artefacts interface (*representation physical*) (Ullmer and Ishii, 2001).

In merging the TUI architecture with graspable user interfaces (Fitzmaurice, 1996), this framework was extended by considering the passive haptic feedback loop, highlighted in Figure 2.1(c), that exists within the physical domain (Ishii, 2008a). Differentiation was made between *'iconic'* aspects of graspable TUI objects and their *'symbolic'* nature, which allowed identification of associated object properties without necessitating digital feedback. This tactile interaction outlined the ability of TUI frameworks to adopt physical objects, which are innately familiar to users, that reinforce the digital information and domain linkage via a priori physical associations. The *representation* coupling is fortified further by TUI systems within the secondary feedback loop that computationally interprets the sensed input data and displays visual (and/or auditory) feedback to the user (Sears and Jacko, 2008).

TUI systems can support a variety of associations between physical objects and digital information. This interlink can be implemented through aspects such as: the use of static media such as images; dynamic media such as animations and video; different material and colour properties; computational functions; simplified data structures and lists; complex data operations and computations; and the use of other devices and remote peripherals (Ullmer and Ishii, 2001).

The tight coupling between physical and digital representations provides TUI architectures with a significant distinction from conventional GUI systems. Whereas the latter is confined to represent information almost entirely in transient visual form with little representational significance provided by the physical components used (such as mice and keyboards), TUI systems, on the other hand, are able to couple digital information to the specific identity, physical position and orientation of artefacts. Thus, enabling the physical manipulatives in TUI architectures to serve central roles in representing and controlling the state of the user interface (Boden *et al.*, 2014).

Moreover, the interactivity provided by traditional GUI computing devices is limited to time-multiplex input devices which control different functions at different times (Fitzmaurice and Buxton, 1997), which enable a sole user to indirectly interface with a GUI environment. These standard multi-purpose peripherals constrain the GUI environments from collaborative interaction and thus hinder the undertaking of collaborative tasks (Magerkurth and Tandler, 2002; Maher and Kim, 2006). In contrast, TUI systems are intrinsically well suited to collocated cooperative work by virtue of their various loci of physical control and thus provide a superior collaborative experience (Martinez-Maldonado, Yacef and Kay, 2015; Barneva *et al.*, 2018). Whilst this limitation has been partially addressed by multitouch interfaces, interaction experiments with multiple users undertaking digital *‘drag-and-drop’* tasks on this platform still proved to be less intuitive than the collaborative experience provided by TUI architectures (Schneider *et al.*, 2011).

2.1.2 Architectural Challenges

Tangible interfaces were thoughtfully defined by Ullmer and Ishii (2001) as “*products of a careful balance between physical and digital representations*”, thus outlining the delicate relationship between these domains that TUI systems need to preserve, and the difficulties imposed in successfully deploying these systems. Tetteroo *et al.* (2013) and Klemmer *et al.* (2006) outline several of the challenges for the development of TUI systems, with emphasis on the careful tangible embodiment of the digital information and the support needed for end-users to utilise the system. The provision of innovative TUI systems present a technological-barrier to surmount, and without appropriate training, users have required direct assistance in order to interact with the tangible interface (Cuendet *et al.*, 2015), whilst others have even indicated signs of fear towards using the system (Alves *et al.*, 2010).

Thus, TUI systems must be programmed intelligently to be able to offer valid feedback to the user and help recognise that the framework has accepted the user input by providing acknowledging feedback. This can be achieved either through positional digital feedback, such as border animation, or by using audio feedback such as tones (Kim *et al.*, 2007). Furthermore, through the digital coupling, users expect to visualise the result of the performed continuous interaction, understanding the relational coherence of their manipulation to the parameter or condition altered. Moreover, the cost burden to implement TUI systems (Lucignano *et al.*, 2014) needs to be justified by a satisfactory replacement to the current procedures. This was exemplified on the *Rasa* (McGee *et al.*, 2002) multimodal TUI system comparison, which identified the advantages for military command post workforces to adopt a TUI architecture over their traditional paper-based procedures. From a usability perspective, TUI systems need to ensure that the consistent interaction expected from users minimises arm fatigue (Jacob *et al.*, 2002), thus not impacting negatively on the users' comfortable experience.

From a design aspect, TUIs necessitate the inclusion of Human Computer Interaction (HCI) principles to be correctly integrated throughout the design (Guan *et al.*, 2014). Systems need to engage users in understanding the presented concepts, whilst also providing feedback that is intelligent and that captures the attention of the user. Furthermore, the appropriate selection of a digital channel for feedback provision needs to be considered using the applicable colours, shapes, sounds, voice and music. The establishment of complementary physical and digital constraints also needs to ensure that the user does not create any invalid language constructs and hence reduce the possibility of invalid input (Marshall, 2007). TUI systems thus necessitate design decisions to be undertaken by a multidisciplinary team, so as to ensure all stakeholders are considered within different project aspects (Alaman, Mateu and Lasala, 2016). Moreover, whilst engaging them to extract high-level tasks and themes, stakeholders should also be included in evaluating the design, interaction, visualisation and testing of the artefact (Shaer *et al.*, 2014).

From a developmental perspective, a TUI necessitates the meticulous combination of physical objects with digital information, as well as developing a communication protocol for these objects to interact with the system through a synchronised programming approach (Greenberg and Fitchett, 2001). The development of tangible prototypes thus requires hands-on skills as well as a good widespread knowledge on diverse areas of IT, computer-science and engineering fields to be able to produce such interfaces (Wang, Moriarty and Wu, 2015). The complex development of these architectures hence requires cross-expertise in software programming, technical skills as well as component tracking algorithms (Macintyre *et al.*, 2003; Shaer and Jacob, 2009; Bottino, Martina and Toosi, 2015). Furthermore, most available TUI platforms are specialized within a particular field, and most often the development of a TUI requires building the system from the ground up (Billinghurst, Kato and Myojin, 2009). The numerous conceptual, methodological, and technical difficulties encountered during development cause further arduous complications due to; "*the lack of appropriate interaction abstractions, the shortcomings of current user interface software tools to address continuous and parallel interactions, as well as the excessive effort required to integrate novel input and output technologies"* (Shaer and Jacob, 2009).

Various frameworks have been designed to aid the average programmer to get to the final goal of developing a TUI, by providing connection manager, identification and simulation frameworks (Greenberg and Fitchett, 2001;

Kaltenbrunner *et al.*, 2005). Additionally, numerous software toolkits and applications have been proposed to enable the development of TUI prototypes by providing application program interface (API) algorithmic functions, in relation to object detection and interactive triggers (Macintyre *et al.*, 2003; Shen *et al.*, 2004; Luderschmidt and Bauer, 2010; A. Wu *et al.*, 2011). Alas, these still require elements of programming knowledge and experience to implement and to further the development and production of even a simple TUI model (Marco, Cerezo and Baldassarri, 2012). Unfortunately, designing and building the physical system also poses its challenges as tangible media may not always being readily available, especially since the objects to be used may be changed according to specific requirements, and commonly developed in three-dimensional (3D) form by graphical artists (Sherstyuk, Treskunov and Berg, 2009). Toolkits such as *Paperbox* (Wiethoff *et al.*, 2013) provide rapid prototyping abilities using paper objects, which, albeit not being precise or durable, allow for better understanding, brainstorming and visualisation of the system at the development stage (Wiethoff *et al.*, 2012). Further yet, implementation of TUI systems presents additional hardware challenges in interfacing and adjusting the electromagnetic or optical camera sensors as well as calibration of the interactive capturing and projection surface (Bottino *et al.*, 2016).

2.1.3 Design Considerations

Apart from mitigating the human and technical challenges described, the successful TUI design is underpinned by the system's ability to provide information to the user in a creative way, integrating the information with the digital objects whilst providing all the information on an appropriate medium (Wang, Moriarty and Wu, 2015). Constructed on the foundational concepts of coupling the physical and digital domain for input and output manipulation, TUI frameworks provide a means for complexity reduction by integrating systems in conjunction with current techniques and tools being used to reduce the TUI development challenge (Fernaeus and Tholander, 2006). To this end, adoption of descriptive toolkits such as; *TUIML* (Shaer and Jacob, 2009), provide a common modelling language which allows developers and designers to be able to discuss, specify and develop TUI architectures.

Design guidelines based on a knowledge-base of implementations, are able to guide TUI architects into selecting the appropriate type of interaction actions on the interactive surface, ensuring that the physical dimensions of tangible objects aid in making interaction styles visible, as well as understanding the different digital information coupling effects to physical manipulation (Stanton *et al.*, 2001). Technical design is also aided by communication models such as; *PEA* (Kaminsky99) which describe a framework for both synchronous and asynchronous communication between embodied agents.

Frameworks such as *PHANToM* (Koleva *et al.*, 2003), provide an abstracted design view which links between the digital information and the physical objects found in TUIs and the different ways in which they can be coupled. Formalising the nature of interaction triggers, concepts such as; *'sensing of information'*, *'configurability of transformation'*, *'lifetime of a link'*, *'cardinality of a link'* and *'autonomy',* are defined to characterise, analyse and design coherent interaction in TUIs. This also enables the classification and differentiation of physical-digital coupling approaches, thus discriminating on the use of *'identifier'*, *'proxy'* and *'projection'* relationships whilst explicitly characterising the *'degree of coherence'* designed (Koleva *et al.*, 2003). The considerations of these relationships can be iterated in design by use of application toolkits that record tangible interaction and enable in depth analysis between TUI designs (Esteves and Oakley, 2011).

These interlinked relationships need to complement the careful design of the physical form-factor for tangible objects to distinctly represent contextual entities. Thus, in contrast to general-purpose peripherals which are intended for *'time-multiplexed'* use, dedicated tangible objects provide an additional link to specific functions in '*space-multiplexed'* interactions (Fitzmaurice, Ishii and Buxton, 1995). Hence, the choice of tangible objects plays a crucial role in effective TUI design. The appropriate selection of familiar objects for the intended user audience, can aid to overcome barriers in the case of user interaction and by facilitating manipulation decisions, TUI systems can overcome user anxiety in interaction (Cuendet *et al.*, 2015). As a result, the innate familiarity with manipulatives can ease the user's cognitive load on control, thus enabling heightened concentration on the domain of interaction (Spreicer, 2011). Toolkits used for creating physical artefacts in ubiquitous computing environments such as *iStuff* (Ballagas et al. 2003), allow for the quick prototyping of unusual physical artefacts without the excessive need to design electronic connections or installing various hardware drivers, aiding developers to iteratively create a physical TUI setup (Avrahami and Hudson, 2002).

Apart from interface and action considerations, TUI architectures also need to ensure a coherent relation between input and output that allows for user trial and error actions, that are done whilst testing and learning using the technology (Sharlin *et al.*, 2009). Moreover, this should be complemented with appropriate system feedback, which via audio, visual and/or movement, is able to provide an indication to users on their actions. The complex definitions of this requirement were abridged by considering the six aspects of effective feedback; time, location, direction, dynamics, modality and expression (Wensveen, Djajadiningrat and Overbeeke, 2004). This characterisation hence aids developers in identifying the suitable interactive instances to provide feedback, whilst also determining the source of information and opportune method to present the output.

The architectural design of TUI systems necessitates addressing the ability to handle multiple inputs as well as multi-user applications, which enable the provision of collaborative interaction with users (Koleva *et al.*, 2003; Eom *et al.*, 2008). Additionally, by adopting different and novel interaction techniques within TUI architectures, developers can augment the effectiveness, intuitiveness and overall interactive experience of using the systems (Beaudouin-Lafon, 2000). Multitouch toolkits such as *PyMT* (Hansen *et al.*, 2009) enable designers to compare and suitably choose interaction techniques to tackle the various interface demands required.

2.1.4 TUI Frameworks

The introduction of TUI frameworks within the field allowed the gathering of similar concepts to mitigate the complex development endeavours (Champoux and Subramanian, 2004). Although *“there is no combined framework that enables prototyping of hybrid multi-touch and tangible user interfaces”* (Luderschmidt and Bauer, 2010), the combined adoption of available TUI frameworks together with various toolkits enables the rapid development of multi-user interactive systems (Mazalek and van den Hoven, 2009).

Aimed towards lowering the threshold for developers of TUI architectures, frameworks such as *Papier-Mache* (Klemmer *et al.*, 2004) and *Synlab API* (Mazalek, 2006) aid developers by removing the underlying technology complications in capturing and identifying object movements using camera support, multi touch surfaces as well as acoustic sensing methods (Mugellini *et al.*, 2009). These integrated application toolkits supply developers with multiple tools for different kinds of input technologies, including computer vision algorithms for identification of barcodes and electronic tags (Klemmer *et al.*, 2004).

Based on these implementations, a specific TUI framework aimed for interactive tabletop surfaces, *ReacTIVision* (Bencina and Kaltenbrunner, 2005) was developed which recognised the physical persistent tangible objects using a dedicated set of marker symbols named ‘*fiducials*’. The latter unique markers are attached to the underside of objects, and the provided framework is able to discriminate and identify objects, as well as provide data about their rotational orientation and position (Kaltenbrunner and Bencina, 2007b). By providing the framework under open source software licenses (GPL, LGPL, BSD), software developers can integrate the computer-vision framework within their TUI architecture by means of call-back methods, thus reducing the development complexity, whilst facilitating the rapid implementation of tangible interfaces (Kaltenbrunner, 2009). Communication frameworks that allowed the API integration of these computer-vision systems have also provided invaluable support towards the popularisation and development of TUI systems. Frameworks such as *ROSS* (A. Wu *et al.*, 2011) and *TUIO* (Kaltenbrunner *et al.*, 2005), employ protocols for the real-time transfer of object data to the computing server, hence providing the architecture with notifications when objects are added, moved or removed from the interactive surface.

As technological innovation is continuously evolving, TUI architectures enable integration with novel developing technologies, providing new interactive techniques, as well as boosting the effective potential of the system (Beaudouin-Lafon, 2000; Hornecker and Buur, 2006; Wang, Moriarty and Wu, 2015). The amalgamation of these technologies using dedicated frameworks, allows the generation of new HCI interaction options and enables them to offer more immersive and natural interaction styles (Hornecker, 2012).

The HCI functionality of Reality Based Interaction (RBI) was integrated with TUI in the framework proposed by Horn *et al.* (2007), which aimed to provide more lifelike user experiences. This combination further reduces the mental capacity required to control and operate the computer interface and directly exploits apriori knowledge and associations (Ras *et al.*, 2014). In alternative work, TUI systems have been coupled with Augmented Reality (AR) to interact with information in more dimensions. This ability allowed users to *"touch the real data",* whilst organising data on an interactive grid (Jacob *et al.*, 2002). Furthermore, the enhanced digital visualisation capabilities brought over by AR, amplified creativity in professional users, since it allowed for early stage design and prototyping of ideas and thus heightened their ability to understand physical phenomena (Nasman and Cutler, 2013; Roberto *et al.*, 2013). The amalgamation of these technologies with TUI has been simplified by integrated frameworks such as; *DART* (Macintyre *et al.*, 2003) that allow for the rapid creation and crude prototyping of combined technologies without expert developmental knowledge.

Tactile and multitouch integration was enabled by the integration of TUI architectures with web applications such as; *TACTIC* (Nunes, Rito and Duarte, 2015) and *Tactive* (Gaggi and Regazzo, 2014). These cross-platform frameworks provide the ability to receive data from detected and identified finger and hand interaction gestures, which provides the ability to augment TUI with haptic information whilst expediting the development and integration process. Sensing-based interaction frameworks further proposed the integration of video and audio tracking, NFC tagging, load sensing, light and even physiological sensing to further the capabilities of TUI architectures (Benford *et al.*, 2005). This framework enables designers to understand the use of embedded or proxemic sensor technologies to move beyond the traditional technical boundaries, thus promoting the creation of more unique and novel ways for users to interact with the TUI architecture (Takama, Ito and Ishikawa, 2015).

2.2 TUI as an Educational Technology

The tight domain coupling afforded by TUI architectures, natively embeds the three representational layers adopted within educational environments, hence providing a more intuitive approach to learning pedagogies (Yonemoto, Yotsumoto and Taniguchi, 2006). By naturally interweaving embodied representation with the learning activity (manipulations) being done, TUI systems are able to ingrain the learning domain through conceptual symbol representation (C. O'Malley and Fraser, 2004). These natural interactions coupled with a shared workspace provide students with a more engaging interactive learning experience whilst leading to fluid collaboration and problem solving (Madni, Sulaiman and Tahir, 2013; Cuendet *et al.*, 2015; Skulmowski *et al.*, 2016). The intrinsic benefits derived from this technology together with its inherent attractive engagement, led to TUI architectures quickly gaining interest within the educational domain (Randelli, Venanzi and Nardi, 2011; Schubert, Serna and George, 2012; Devi and Deb, 2017).

2.2.1 Teaching and Learning

Whilst capturing children's interest, TUI systems provide a technological enabler to active learning pedagogies by allowing students to freely interact with the teaching and learning progress (Antle, 2007). Furthermore, the novel interactive techniques employed in TUI architectures are also able to motivate children in learning whilst boosting their design and creativity skills (Nasman and Cutler, 2013). Making use of multimedia integration, TUI systems further present the ability to simultaneously convey teaching and learning on different sensory channels, thus augmenting their applicability in the educational domain (Tanhua-Piiroinen, Pystynen and Raisamo, 2010; Ukil and Sorathia, 2014).

This has led TUI architectures to further educational technologies by providing a means to aid students in: *"development, contributing to their motor aspects' improvement, sensory engagement, accessibility, collaborative activities and* *understanding of the world around them"* (Zuckerman, Arida and Resnick, 2005). These positive impacts on learning, lead students to develop a heightened cognitive ability when engaging with TUI systems to understand concepts (Tanhua-Piiroinen, Pystynen and Raisamo, 2010; Sorathia and Servidio, 2012), a hypothesis that was further evaluated by Lucignano *et al.* (2014). The concept was taken further by Schneider and Blikstein (2016), who analysed the overcoming of limiting beliefs on cognitive ability on native-speaking students, who gained deeper understanding of subjects without the necessity of overcoming a barrier of technical jargon (Schneider *et al.*, 2013).

The adoption and use of conventional desktop GUI systems as an educational technology commonly requires students to maintain focus on their entire field-of-view so as to ensure no information displayed goes unnoticed. In contrast, TUI systems are able to provide an inherent differentiation and association of the projected information directly within the interactive area (Ishii, 1998). This design offers the reduction of the mental and cognitive load imposed on students during interaction, which in turn further aids with the ability to engage in '*rapid epistemic'* experimental learning approaches (Ras *et al.*, 2014). Furthermore, by supporting a more 'hands-on' student-centred approach, TUI systems aid students in bridging the gap between the theory and practice (Madni, Sulaiman and Tahir, 2013; Cuendet *et al.*, 2015).

TUI systems further interlink the virtual and physical domains by allowing the direct manipulation of physical artefacts to alter the digital representations (Shaer, Horn and Jacob, 2009). The use of familiar objects as controlling manipulatives, together with the enriched interactions afforded by these physical elements, have a vital impact on students' ability to comprehend associations during learning (Maquil and Ras, 2012). This aligns with the observation undertaken by Rieser *et al.* (1994) who demonstrated how physical movement enhanced children's thinking and learning, including helping children categorise and recall tasks of perspective thinking and spatial imagery. This allows students to develop better communication and comprehension, ensuring better focus on the topic and better problem-solving abilities, whilst enjoying the educational activity (Roldan-Alvarez *et al.*, 2014).

The embodiment of control in tangible objects necessitates students to interact with TUI architectures by using both their motor and spatial skills (Schneider *et al.*, 2011; Markova, 2013). The cognitive skills employed in these manipulations allows children to enhance their eye-to-hand coordination, distance definition as well as physical shapes discrimination (Kim and Maher, 2008; Quarles *et al.*, 2008; Cuendet, Bumbacher and Dillenbourg, 2012). The haptic perception provided by TUI during motor skill learning has, apart from making the technology more approachable to use and understand, further been associated with positive effects in other cognitive areas (Wulf, Shea and Lewthwaite, 2010; Skulmowski *et al.*, 2016). O'Malley *et al.* (2004) have identified improvements in children's ability to count and link tags to words, correlations that were further expanded to general mathematical problem-solving skills and metacognition (Antle, 2007; Skulmowski and Rey, 2017). This collaborated the findings by Bransford and Schwartz (1999) who argued that *"students who analyse contrasting cases can cultivate their perceptual skills to develop and understand the deep structure of a problem",* and confirming the suitability for TUI to provide the capacity for '*concrete experimentation'* and *'active experimentation'* (Kolb, Boyatzis and Mainemelis, 2000; Ozkal *et al.*, 2009).

During various TUI experiments designed in line with the Pedagogical Framework Learning (PFL), it was noted that participants using a tangible interface were able to memorize and recall a model better than others studying the same model designed over conventional printed paper (Schneider and Blikstein, 2015). Moreover the academic performance, measured in terms of memorization and understanding, further improved if TUI systems were adopted to explain a topic prior to exposing students to studying the content from a text book (Hansen and Halskov, 2014). The disparity was attributed to the ability of TUI architectures to convey teaching and learning in an interactive multi-channel approach, in contrast to traditional lecturing which utilises a single verbal channel to both write and read material whilst simultaneously listening to lecture explanations (Schneider and Blikstein, 2015).

When analysed with respect to GUI based devices, TUI architectures lower the participation threshold for students hence directly promoting collaborative interaction (Scarlatos, Dushkina and Landy, 1999; Catala *et al.*, 2011; Madni, Sulaiman and Tahir, 2013). This ability contrasts to the experience provided by conventional laptops and tablets, whereby the control hardware devices encourage a single student to take over interaction, intrinsically limiting other team members' participation and learning experience (Stringer *et al.*, 2004; Terrenghi *et al.*, 2006). Nevertheless, the general agreement on collaborative effectiveness in TUI has been challenged by Ras *et al.* (2014) who noted the limitation of TUI architectures to handle large cohorts of students. This resonates with the design challenges outlined in section 2.1.2 which outlined the need for comprehensive considerations to be implemented within the design of TUI architectures to ensure they are effective within educational contextualization (Kuzuoka *et al.*, 2014).

2.2.2 Primary Education

The attractive, engaging, and playful attributes of TUI architectures have had an intrinsic appeal to implementation within early-stage and primary education from the earliest developments (Perlman, 1976; Dumpit and Fernandez, 2017), in an attempt to provide young children an entertaining and enjoyable approach to learning (Price *et al.*, 2003). In direct relation to alternative educational technologies, young children of which notably mostly were girls, are more likely to approach and actively engage with a tangible programming exhibit (Horn *et al.*, 2009).

By ubiquitously embedding and integrating technology into frequent activities and studies, TUI architectures provide an augmented experience for children, encouraging learning through exploration whilst enabling the association of information with everyday physical items (Terrenghi *et al.*, 2006). In addition, TUI setups expose young children to discovery-oriented, open-ended learning and logical understanding (Edge and Blackwell, 2006), which triggers early thinking processes and further development of their cognitive skills (Kikin-Gil, 2006). This has led to the observation by Shaer and Hornecker (2009) that "*Computationally enhanced construction kits can make concepts accessible on a practical level that are normally considered to be beyond the learner's abilities and age-related level of abstract thinking".*

In using TUI architectures, children are engaged in collaborative environments during playful and exploratory activity, further aiding their young minds in developing social interaction skills (Farr, Yuill and Raffle, 2010; Sylla *et al.*, 2012). In turn, besides playing with other children, pupils exhibit enhanced motivation and attention during the classroom session, leading to promoted creativity and memory abilities to imagine and recall scenarios (Sapounidis and Demetriadis, 2013; Devi and Deb, 2017). Moreover, the collaborative experimentation allows children to explore different combinations through tangible manipulatives, providing the ability to find different, better and maybe more unique solutions whilst learning from experience through represented digital data (Beattie *et al.*, 2006; Tseng, Bryant and Blikstein, 2011).

This creativity was evident in TUI implementations used to teach children music by being able to create musical scores using a token-and-constraints *Neurosmith Music Blocks*^{TM} assembly (Lackner *et al.*, 1999). Simple music annotations were also successfully engaged with in the implementation by Waranusast *et al.* (2013), which allowed children to place and manipulate musical notes on a surface and hear the melody audio through speakers, providing an interactive way to learn. A similar cross-domain deployment was undertaken by *BeatTable* which combined the teaching of music and mathematics by associating *'ratios'* and *'proportions'* to create musical rhythmic compositions by fusing auditory and visual media (Bumbacher *et al.*, 2013). The success in elementary mathematics also proved to be helpful in the teaching and learning of summation, as well as allowing learners to explore the concepts of surface area and volume of 3D objects (Girouard *et al.*, 2007). These results contradicted the preliminary findings by Uttal *et al.* (1997) who argued that mathematical concepts are not acquired by tangible interfaces due to the various misunderstandings generated from the technology.

In visual arts education to children, *Chromarrium* (Rogers *et al.*, 2002) was developed to allow primary school students to experiment with colour mixing by manipulating coloured blocks together, whilst obtaining visual feedback on an adjacent screen. Another TUI architecture employed an *I/O Brush* tool (Ryokai, Marti and Ishii, 2004), modelled on a physical paintbrush, which enabled children to draw on an interactive surface by capturing colours from moving images using an embedded video camera. This enabled young children to draw in a novel and unconventional colour palette by using the natural aspects of colour, texture and movement captured directly from live objects. Ryokai et al. (2004) observed that *“coupling a familiar physical action with an unfamiliar digital effect”, proved to be “effective in causing children to talk about and reflect upon their experience”*. A cross-domain TUI deployment between art and music was achieved in *Jabberstamp* (Raffle *et al.*, 2007), whereby children could create drawings with embedded audio recordings using a combination of toys as input and output tangible devices. A combination of active and passive tangible objects was also employed in a different teaching context by *“Ely the Explorer”* framework (Africano *et al.*, 2004), whereby a collaborative mixed-technology system was developed using touch-screens, tangible toys, RFID-tagged cards and physical selection knobs to interact with learning about geography and culture while practicing basic literacy skills.

In literacy education, the interactive multimodal TUI tabletop in *Read-It* (Sluis *et al.*, 2004) was designed to entice young children in developing their reading skills by engaging within a collaborative game. In primary education, students’ *WebKit* (Stringer *et al.*, 2004) has allowed pupils to learn rhetorical skills by embedding RFID tags on tangibles. This constructive assembly model was able to support children in preparing, ordering and connecting argumentative statements by sequencing TUI artefacts whilst providing interactive feedback (Stringer *et al.*, 2004). A different contextualisation of the *WebKit* TUI system was adopted for the collaborative interaction using RFID tagged artefacts to exploratively navigate and familiarise with formalising query phrases for searching through the World Wide Web (WWW), outlining the flexibility of the TUI architecture (Stringer et al., 2005).

Early literacy education has deployed TUI architectures in the compelling application of storytelling, within which the latter exploit books, regular toys and playing environments to augment the children's experience and learning capabilities whilst helping to develop interpersonal and story-related skills (Hourcade *et al.*, 2002). Amongst the earliest developments was the constructive assembly developed in *Triangles* (Gorbet, Orth and Ishii, 1998) which developed pre-configured data/voice recording artefacts and allowed students to manipulate a storyline collaboratively. A similar collaborative effort embedded tangibles in wearable jewellery, where interactive beads contained electronic images to create a wearable tangible necklace by trading beads between classmates (Barry, 2000).

A different approach was taken by *Storymat* TUI architecture (Ryokai and Cassell, 1999), which made use of traditional toys embedded with RFID technology to permit children to create and record stories by naturally playing together on an interactive play mat. These digital captures were subsequently played back to the class using audio and visual projections whilst allowing children to edit collaborative stories (Ryokai and Cassell, 1999). A TUI tabletop architecture, *The Tangible Viewpoints* (Mazalek, Davenport and Ishii, 2002), provided an intriguing ability to navigate through different viewpoints of a story by manipulating physical objects whilst interacting with the interface. Such setups allow children to identify and associate attributes, text and articular perspectives to tangible characters, providing children with the ability to argue and interpret storylines from different aspects (Tanenbaum and Tomizu, 2008). A more immersive setup was developed in the *Kidstory* architecture (Stanton *et* *al.*, 2001), which allowed children to physically collaborate on story design whilst physically navigating within wall projections on an interactive *'magic carpet'* floor surface (Fraser *et al.*, 2003).

The introduction to technical and programming concepts using TUI architectures has also been well explored in education (Sapounidis and Demetriadis, 2013). Implementations of this technology aimed to support programming constructs via a constructive assembly of tangible programmable elements (Suzuki and Kato, 1993; Qi, Demir and Paradiso, 2017). Collaboratively interacting with a sequence of electronic blocks, children can design programming routines, interact via buttons and LEDs as well as customise commands using the *Logo* educational programming language (Suzuki and Kato, 1995). Similar constructive assemblies like; *Electronic Blocks* (Wyeth and Purchase, 2002), *Digital Construction Sets* (McNerney, 2004) and *Tern* (Horn, Solovey and Jacob, 2008) made use of interactive shaped blocks, each uniquely representing an analogous programming instructions. This enabled children to engage with the basics of a sequential programming language by physically concatenating blocks to develop commands according to the tangible artefact's physical shape (Horn *et al.*, 2009).Commercialising successfully this TUI architectural implementations was the *LEGO Mindstorms*TM robotic toolkit, conceptualised by Martin (1995), which used programmable electronic bricks to physically interact with electronic sensors and actuators modules, allowing students to develop robotic programmed routines.

Another early approach to educating children on programming and robotic concepts was by adopting a kinetic memory TUI architecture by allows students to interact by physically moving and repeating a set of guiding motions and gestures in a 'demonstration' approach to programming (Cypher *et al.*, 1993). Using palm-sized tangible objects with inbuilt computational, sensory and actuation capabilities, TUI systems such as *BitBall* (Resnick *et al.*, 1996) and *Curlybot* (Frei *et al.*, 2000) are able to record the motion created by children and replay back the physical motion. Apart from aiding children to learn kinematics, these educational TUIs are also able to aid in describing geometric design gestures and narrative (Frei *et al.*, 2000).

The two TUI architectural concepts for teaching programming and robotics were combined in a the *Topobo* system (Raffle, Parkes and Ishii, 2004), which produced a programmable constructive assembly using kinetic memory components to record and replay motions. This enabled the construction of dynamic biomorphic figures which children could program using kinetic memory and replay the motion indefinitely hence aiding to explain dynamic systems (Raffle, Parkes and Ishii, 2004). By adopting a '*free play'* approach to teaching computer programming, TUI systems inherently encourage children to learn by experimentation and exploration, consequentially giving the educational technology an enjoyable perception from younger audiences (Nusen and Sipitakiat, 2012). A detailed review of tangible architectures for introducing children to programming concepts is further provided within section 5.7.1.

2.2.3 Special Education

The rich cognitive and physical learning environment generated by TUI interfaces have also been developed to support the teaching and learning for young children with special educational needs (Starcic, Cotic and Zajc, 2013; Barajas, Al Osman and Shirmohammadi, 2017). By engaging children with physical interaction during hands-on activity, TUI architecture provide peculiar benefits to address the individual differences and needs of students since the technology intrinsically adopts to the interaction pace of the user, provides indirect training on perceptual-motor skills, as well as engages the toddler in a more immersive sensorial experience (Virnes, Sutinen and Kärnä-Lin, 2008; Shaer and Hornecker, 2009). Moreover, these benefits increase the children's opportunities to develop cognitive, linguistic and collaborative social learning skills whilst heightening the enthusiasm and enjoyment aspects of education (Sitdhisanguan *et al.*, 2012).

This was attested by Farr *et al.* (2010), who designed a collaborative TUI architecture for children who suffer from an Autistic Spectrum Condition (ASC) by using the commercial *Topobo* and *LEGO Mindstorms*™ TUI platforms. The collaborative nature of TUI architectures allowed for sharing of robotic components between students with ASC, enticed social interaction, promoted cooperation and association between engaged students and consequently aided in the development of social skills (Mazalek and van den Hoven, 2009; Farr, Yuill and Raffle, 2010; Roldan-Alvarez *et al.*, 2014). Furthermore, the ease-of-use and computer-based learning capabilities of TUI architectures present low-functioning autistic children with an enhance tangible manipulation environment that adopts familiar physical objects whilst using simplified manipulation skills (Jacob *et al.*, 2002; Karanya Sitdhisanguan *et al.*, 2007). This leads to a higher task engagement rate and better exploratory learning experience to be undertaken by children suffering from ASC (Sitdhisanguan *et al.*, 2008; Skulmowski *et al.*, 2016).

More specialised TUI architectures were created within the *Linguabytes* (Hengeveld *et al.*, 2008), *CoinBeam* (Mittal *et al.*, 2015)*, DataSpoon* (Zuckerman *et al.*, 2016) projects. The former aims to aid young children in speech therapy by interactively engaging toddlers with communication disorders with more intuitive storytelling activities (Hengeveld *et al.*, 2009), whilst *CoinBeam* aids intellectually challenged students to grasp the concept of money (Mittal *et al.*, 2015). The *DataSpoon* architecture on the other hand is aimed to aid children with cerebral palsy and motor disorders to master self-feeding capabilities by digitally capturing the sensed 3D motion, which help to evaluate and monitor the improvements in children's movement skills (Zuckerman *et al.*, 2016). The capabilities of a TUI system to digitally record interactions and log manipulation data (Sharlin *et al.*, 2002), has further been exploited by to aid in diagnostic assessment of cognitive spatial abilities and monitor the children's development progress (Westeyn *et al.*, 2008; Sharlin *et al.*, 2009).

2.2.4 Secondary Education

TUI architectures were also developed as an educational technology to support high school institutions with subjects in which secondary student's commonly struggle to comprehend (Randelli, Venanzi and Nardi, 2011). Within this domain, TUI instances were developed to aid teaching and learning via simulations of a topological nature (Price *et al.*, 2003; Shaer and Hornecker, 2009). By manipulating physical symbols, students are enabled to explore innovative problem-solving solutions, by simulating outputs and thus reducing the cognitive stress needed to consider all the possible options of a problem (Schneider and Blikstein, 2013). Furthermore, carefully designed TUI architectures enable students to utilise the system's control inputs within instinctive manipulation, which reduces the mental effort and focus needed for operation, and in turn positively influences the students' creative design process in solving tasks (Chandrasekera and Yoon, 2015). These effects were evidenced in the *Combinatorix* architecture (Schneider, Blikstein and Mackay, 2012), which enabled students to understand the basics of combinations and probability using tangible letters on an interactive tabletop setup.

Scientific concepts in optics were explained using the *Illuminating Light* interactive surface architecture (Underkoffler and Ishii, 1998), which provided a learning environment for laser-based optical and holographic topologies whilst reducing the need for scientific equipment and lasers. This TUI architecture simulated light-beam animations being diverted by tangible prisms and mirrors to help students understand the phenomena of reflection, refraction and absorption augmented with digital telemetric data such as distances, angles, and path lengths (Underkoffler and Ishii, 1998). In chemistry, the *Augmented Chemistry* (Fjeld *et al.*, 2004) TUI architecture integrated with Augmented Reality (AR) to provide students the ability to digitally visualise and interact with virtual molecular structures thus enabling better understanding of compounds from an XML-based database (Almgren *et al.*, 2005; Fjeld *et al.*, 2007).

In biology, a token-based TUI architecture was developed which consisted of modular *Thinking Badges* (Borovoy *et al.*, 1996), embedded with digital information displays and proximity communication that could be worn by students as name tags. Contextualised within a virus epidemic scenario, students were able to engage in *'participatory simulations'* to model contamination spread in different instances (Neulight *et al.*, 2007). This simulation further allowed the data capture and visualisation of social interaction patterns between students, thus providing insight and provoking analytic discussions (Colella, Borovoy and Resnick, 1998; Resnick and Wilensky, 1998; Colella, 2000). Furthermore, the TUI development of *AutoGrasp* (Agrawal and Sorathia, 2013) allowed secondary education students to engage with astronomy concepts whilst interacting with helispherical symbols representing the Earth and moon in a bid to visualise phenomena such as seasons and eclipses using digital representations of rays and shadows.

Other TUI examples aimed to intrigue and engage both secondary students and general public to understand historical events. With the TUI actuated assemblies of *Navigational Blocks* (Camarata *et al.*, 2002) users were able to formulate queries on event details relating to moments in American history, whilst physically interacting with attracting or repelling blocks that guide students to the correct answers. A workbench TUI architecture was developed on the other hand to educate students and visitors on the history of Nottigham Castle, whereby by means of an interactive flashlight, virtual images were projected on a sand pit, revealing localised animations and narrations (Fraser *et al.*, 2003).

From a technical perspective, TUI architectures have also been used to introduce object-oriented programming (OOP) languages to secondary students by using a gamified approach (Rodríguez Corral *et al.*, 2014). Adopting the *Sifteo cubes* (Merrill, Sun and Kalanithi, 2012) constructive assembly, students interacted with *C#* programming instructions by physically sorting the adjacency of cubes, which in return displayed visual feedback on embedded screens (Rodríguez Corral *et al.*, 2014).

2.2.5 Higher Education

Within the field of Higher Education, the development of TUI architectures has been largely stifled with only a handful of systems partially intended to aid in the teaching and learning of tertiary and higher education students (Schneider and Blikstein, 2016). Furthermore, the majority of these TUI architectures are an extended adoption of TUI setups developed in other domains (Mazalek and van den Hoven, 2009), and thus tend not to encompass the peculiar necessities demanded by HEI students within computational science and technology-based concepts.

Whilst still being able to provide an experimental environment for students, most of these architectures focus on the integration with other technologies such as; Haptic and AR to cater for the contextual complexity of higher education (Vidarte *et al.*, 2010), thus failing to adopt the TUI framework so as to cater for the peculiar HEI requirements. This was evidenced in the TUI architecture proposed by Vidarte *et al.* (Vidarte *et al.*, 2010), which utilised digital blocks upon which *ARToolkit* markers (Kato and Billinghurst, 1999) were attached and recognised by a desktop camera and the digital projection visualised on a PC monitor. This framework utilised simple pattern blocks as tangible interactives which albeit being widely used hands-on learning tools (Yonemoto, Yotsumoto and Taniguchi, 2006), fail to embody physical representation of the coupled digital information (Cuendet *et al.*, 2015). Whilst being able to teach the abstract concepts of recursion and functional programming using simple block stacking manipulations and the TUI/AR architecture virtualises the output on external devices, thus violating the TUI concepts of perceptual coupling (Ishii *et al.*, 2012). Mixed evaluation results were also achieved when adopting TUI architectures in conjunction with AR for learning molecular stuctures (Fjeld and Voegtli, 2002; Weghorst, 2003; Gillet *et al.*, 2004; Asai and Takase, 2011). These developments identified AR markers attached to blocks or cards which were augmented on a PC monitor with digital data on the molecular activity and electrostatic fields in compounds (Fjeld *et al.*, 2004; Gillet *et al.*, 2005).

A similar omission in perceptual coupling was also done in the token and constraint *Tangible Query Application* (Ullmer, Ishii and Jacob, 2003) architecture, which aimed to provide an interactive environment for database query, views and boolean operations. Albeit using a horizontal surface for visualisation, the student's interactions were limited on physically distinct constraints which are mapped on '*tracks'* and *'slots'*. Whilst this approach was feasable for interaction with simple database queries, the design oversights led to no performance advantage being measured during evaluation over traditional GUI systems (Ullmer, Ishii and Jacob, 2005). The need for appropriate TUI design considerations prior to deployment within HEI was also outlined following the implementation of *GraphMaster* (Schweikardt *et al.*, 2009) constructive assembly. Whilst the latter was able to tangibly aid in visualising components in graph theory via dedicated props, the limited considerations of digitial embodiment and appropiate feedback failed to popularise the system (Schweikardt *et al.*, 2009).

Within the field of neuroscience, the props-based *3D Neurosurgical Visualisation* (Hinckley *et al.*, 1994) and the tabletop *BrainExplorer* (Schneider *et al.*, 2013) TUI architectures, aimed at providing a hands-on experience to students by allowing the manipulation of 'scalpels' and 3D printed anatomical models whilst visualising neural pathways in cross-section (Hinckley *et al.*, 1997). These deployments were evaluated to instil curiosity in surgeon students and aid students using the TUI prior to studying from text-books in *"memorizing scientific terminology, understanding a dynamic system, and transferring knowledge to a new situation"* (Schneider and Blikstein, 2015; Schneider *et al.*, 2016). Conversely however, the inability of TUI systems to account for the interaction complexity required in understanding the processes exposed by the *G-nome Surfer* framework (Shaer *et al.*, 2010) failed to deliver equally positive results, with lack of advanced options curtailing the educational effectiveness of HEI students (Arif *et al.*, 2016).

Within the architectural domain, the development of prototyping models has always sought the advantages brought over by tangible visualisation to enable the iterative redesign of urban planning following evaluation feedback (Maquil, Psik and Wagner, 2008). Enhancing this concept further, pioneering TUI architectures, such as *Urban Resource Planner* - *URP* (Underkoffler and Ishii, 1999) have coupled digital representations to provide students with augmented simulated information such as wind-flow, illumination, shadows, temperature. Apart from collaboratively manipulating the configuration of building models, the interactive surface TUI architecture employs dedicated tangibles to allow architectural students to interact and visualise the dynamic effects of altering time of day and wind direction (Underkoffler and Ishii, 1999). These concepts were extended in the tabletop TUI developments such as; *MouseHaus Table* (Huang, Do and Gross, 2003) and *ColorTable* (Maquil, Psik and Wagner, 2008) which allowed students to collaboratively interact and envisage building designs in tandem with digital augmentation of pedestrian computational simulations and mixed-reality virtualisation.

Two further setups proposed by Fernando et al. (Fernando, Dupre and Skates, 2016) employ thermal cameras, thermocouple sensors together with a TUI architecture to illustrate civil engineering students the psychrometric effects of wind and water temperature as well as material thermal transfer. A similar laboratory setup was adopted by *GeoTUI* (Couture, Rivière and Reuter, 2008), which when compared to traditional GUI exercises, allowed students to undertake the cutting of virtual lines in geographical subsoil map more intuitively using associative tangibles tools. Conversely however, mixed evaluation results were obtained when adopting tangible models to teach 3D modelling techniques on Computer Aided Design (CAD) software within Industrial Design programmes (Hejlesen and Ovesen, 2012).

The fluctuations of results and success in literature on TUI deployments within HEI highlights the divergence of requirements needed for successful design of TUI architectures for higher education with respect to earlier educational stages. The need to retain simplistic interactions albeit the domain complexity was identified as essential by Song *et al.* (2014) to avoid overwhelming students with multimodal information, leading to adverse educational results in medical school training. Similar injurious results were obtained when delivering mathematical concepts through TUI, where the inability to provide an intuitive coupling between physical objects and the digital domain hindered the students' educational experience (Uttal, Scudder and DeLoache, 1997). The abstruse aspects of HEI education nevertheless, pose an intrinsically difficult challenge to resolve the digital and physical embodiment in TUI architectures (Clements, 2000). Furthermore, whilst TUI systems intrinsically promote collaborative interaction, the improper design for this functionality may conversely hinder the collective learning experience provided (Stanton *et al.*, 2001; Sluis *et al.*, 2004). Thus, the design considerations for TUI architectures in HEI demands the need for "highly specialised TUIs" to cater for the domain complexity (Sharlin *et al.*, 2004).

Teaching young adults in higher education institutions (HEI) becomes further challenging since the subject matter becomes more complex and abstract (Fernando, Dupre and Skates, 2016). This is further compounded by the complex and abstruse concepts, towards which traditional media such as; textbooks, images and video fail to provide adequate visualisation (Schneider *et al.*, 2013). Academics and Educators thus, need to simplify a problem by abstracting complexity from raw data or concepts and displaying it in a 3D tangible and physical form without losing any detail (Tetteroo, Soute and Markopoulos, 2013). This makes knowledge more engaging and naturally understandable and thus changing the way humans interact with information holds potential for aiding the teaching and learning abstract concepts (Schneider *et al.*, 2013).

Despite all the deterring challenges to successfully adopt TUI in HEI, the notorious difficulties to both teach and understand concepts in this domain, led stakeholders to constantly seek TUI interactions as a way to aid students in comprehending threshold concepts (Vidarte *et al.*, 2010; Schneider *et al.*, 2011; Schubert, Serna and George, 2012; Morán *et al.*, 2013; Cuendet *et al.*, 2015). This led to an increase in research pressure to continue developing such technology so as to cater for such complex subjects (Ras *et al.*, 2013). In particular, TUI architectures are sought after as they provide students a natural way of learning by simultaneously engaging their senses through vison, audio and touch (Zuckerman, Arida and Resnick, 2005).

Furthermore, TUI architectures provide learners with the possibility of experimenting with the subject being taught by interacting with a digitally coupled physical model, hence enabling deeper conceptual understanding whilst exploring the underlying mechanisms (Jacob *et al.*, 2002; Marshall, 2007; Garber, 2012). The ability to manipulate and construct real life physical objects or models whilst focusing on a different task provides students with the possibility to apprehend more complex scenarios as elucidated by Marshall (2007) in stating that; *"three dimensional forms might be perceived and understood more easily through haptic and proprioceptive perception of tangible representations than through visual representation alone".* TUI architectures furthermore increase collaborative group work capabilities, which together with the possibility of additional technology integration can aid simplification and understanding of complex concepts (Schneider *et al.*, 2011).

Notwithstanding these innate advantages, the application of TUI to aid teaching and learning abstracted concepts has obtained mixed results within the literature. Whilst tangible interfaces proved better than conventional technology for complex problem-solving tasks (Schneider *et al.*, 2011), problems were being solved at a slower rate by students (Catala *et al.*, 2011). Manipulation of tangible cubes and models has often also demanded increased effort by students, leading TUI architectures to impede student focus by requiring unintuitive controlling actions (Goh *et al.*, 2012; Shaer *et al.*, 2014). This was outlined by the inability for TUI interactions to effectively aid medical students in understanding anatomical concepts (Skulmowski *et al.*, 2016).

Skulmowski *et al.* (2016) further argue that the advanced motoric skills required to interact with complex data and topics render TUI architectures inadequate with respect to conventional approaches. Moreover, despite the high costs needed to distribute TUI technology in lecture halls (Lucignano *et al.*, 2014), TUI architectures are limited in their scalability capabilities to handle large number of tangible objects or providing large interactive surfaces. These inherent limitations thus constrain TUI architectures to effectively cater for the complex and large examples commonly required to address abstract concepts in HEI (Shaer and Hornecker, 2009).

Chapter 3
Research Methodology

3.1 Introduction

Founded on the research challenges uncovered within the limited literature on adopting tangible user interfaces in higher education, this study aims to empirically analyse the effectiveness and suitability of TUI systems as an educational technology within such context. Based on the lack of grounded designs and consistent results in HEI literature, together with the researcher's motivation outlined in section 1.1, this research explores the interactive design capacity of TUI systems to overcome the challenges of educational stakeholders in teaching and learning abstract and complex concepts.

To this extent, the research question investigated within this study;

> ***Are tangible user interfaces an effective and suitable technology to explain abstract and complex concepts in higher education?***

was formalised further through a set of subordinate research questions in line with the research categorisation defined by Hendrick et al (1993) and directly mapped to the investigated contributions of this study:

- **Normative**: Are TUI tabletop architectures suitable for use in higher educational institutes?
- **Impact**: What are the effective interactive methods that can be employed in TUI frameworks to aid in the teaching and learning of threshold concepts within computational science and technology subjects?
- **Correlative:** What factors influence the acceptance of TUI systems in higher education?
- **Correlative:** How does the design of tangible elements aid in the teaching and learning pedagogy of abstract and complex concepts?

3.2 Research Setting

In line with the inherent nature of the investigative research application, this study is primarily conducted at Middlesex University and opportunistically based within its Malta and London campuses. The identified campuses provide access to a yearly population of approximately 300 computational science and technology students throughout the duration of this research, studying in diverse field specialisations at either undergraduate or postgraduate levels. This educational setting further provided access to a body of faculty academic experts, which constitute a valuable knowledge base for elicitation of technical or specialised knowledge within this study.

The physical nature of this higher educational institution critically provided the ability to interact with participants during the design and deployment of research procedures. Hence, this context provides the capability of furthering the initial research problem by means of an exploratory research methodology within the domain (Amaral et al., 2011). To this end, based on an overarching agile methodology, the research methods and procedures designed could initially be derived from identified literature in similar contexts, and subsequently, iteratively refined through the incorporation of practical and empirical experience obtained within the agile cycles (Ayash, 2014).

Whilst providing invaluable support to easily engage with the student population throughout the study, the innate characteristic of the educational setting described above imparts a significant restraint towards the timing of research activities. Consequently, the deployment of experimental interventions and evaluation methodologies can only be undertaken during lecturing term-times in line with the academic calendar employed within the university. This contextual constraint imparts a dominating timeline for undertaking agile iterations throughout this research, hence leading to the concurrent and overlapping adoption of research methodologies aimed at answering the distinct perspectives identified within the four subordinate research questions above.

3.3 Quantitative Research Methodology

The study is primarily conducted through a post-positivist philosophical assumption, whereby by means of a scientific approach, quantitative research methodologies are designed and adapted for answering the identified research questions (Ryan, 2006; Fox, 2008). This paradigm is adopted along with the core research question of this study whereby the research aims to experimentally quantify, collect and statically analyse data to validate the established hypothesis through a systematic, rigorous and tightly controlled inquiry process (True and Bryman, 1990; Creswell, 2014). To this end, this section outlines the methodology detail adopted for the first three subordinate research questions investigated which are subsequently investigated in chapters 4, 5 and 6 respectively.

3.3.1 Research Design

To support the varied perspectives sought by these hypotheses, the design and development of a systematic and structured research methodology is appropriately undertaken for the investigation of each subordinate research question formalised. To this end, this section distinctively structures the details the research design adopted for the core contribution within this study together with the complementary research methods utilised to answer the subsequent research questions addressed along this research.

3.3.1.1 Educational TUI framework designs for HEI contexts.

The research question behind this contribution explores “what are the effective interactive methods that can be employed in TUI frameworks to aid in the teaching and learning of threshold concepts within computational science and technology subjects?”. Underlying this pursuit is a formalised research hypothesis which investigates:

Can the use of TUI frameworks (independent variable) in HEI to influence the knowledge gain of students (dependent variable) whilst learning abstract and complex concepts?

The directionality problem of this hypothesis is addressed through the design of a quantitative quasi-experimental research methodology which aims to manipulate the independent variable of TUI frameworks as the educational technology. This is done through the use of intervening variables involving tangible elements and interactive design whilst monitoring and assessing the effect imparted on the dependent variable of student knowledge gain. Moreover, the research methodology involves the undertaking of a between-subjects design. This entails the comparison between an experimental group receiving an intervention, through the use of TUI, and a control group that is not exposed to the proposed technology but instead is engaged with conventional educational technologies commonly adopted in HEIs (McBurney and White, 2010).

The understanding of meaningful learning imparted by the investigated educational technologies and pedagogies is conducted in line with the learning models proposed by Jarvis (1992, 2014) and Novak (1998, 2010) which measures learning as the integration obtained from the newly acquired knowledge in relation to prior knowledge (Hay, 2007). To this end, a pre-test/post-test quantitative design is considered, whereby the a priori knowledge of participants is initially measured to develop an individualistic baseline from which learning and knowledge gain can be calculated and assessed (Hay, Kinchin and Lygo-Baker, 2008).

3.3.1.2 Technology Acceptance Model for Educational Technology

The subordinate research question behind this contribution examines "What factors influence the acceptance of TUI systems in higher education?". This inquiry is addressed through a formalised research hypothesis which aims to study:

Is the use of TUI frameworks (independent variable) in HEI a suitable technology (dependent variable) whilst learning abstract and complex concepts?

In similar fashion to the core contribution of this research, this hypothesis is addressed by means of a quantitative quasi-experimental methodology, which investigates different educational technologies as an independent variable used in teaching and learning within higher education. To this extent, in tandem with the experimental interventions done on the proposed TUI frameworks and the respective conventional educational technologies setup as control, a between-subjects research methods design is implemented in this study. Based on established literature work in assessing and modelling technology acceptance (Davis, 1989; Venkatesh and Fred D Davis, 2000; Venkatesh and Bala, 2008), the behavioural intention of students is studied as the dependent variable of the hypothesis.

Whilst the principle components of TAM models have been well-validated to model user behavioural (Turner *et al.*, 2010; Mortenson and Vidgen, 2016), the subordinate question exposes a research gap in current TAM literature; to model the adoption of educational technologies in HEI (Dumpit and Fernandez, 2017). To this extent, the research design proposes and investigates a set of determining constructs as intervening variables to acquire an understanding of the perceived suitability of educational technology by higher education students.

Exploiting the cyclic nature of academic terms in the university research setting, a two-stage design is implemented for this research. This methodology provides the ability to screen ‘promising’ hypotheses during a first-stage model analysis which are then subsequently investigated during a second-stage research design (Zehetmayer, Bauer and Posch, 2005; Elsawah, 2018). Thus, the instrument development within this research is successively refined based on a statistical analysis obtained from a larger investigation of possible correlative hypotheses for analysing educational technology. Ultimately, the validated instrument is deployed within an HEI context to evaluate the research hypothesis of determining the suitability of adopting TUIs as an educational technology to aid the teaching and learning of abstract concepts.

3.3.1.3 A TUI interactive tabletop architecture to support HEI contexts.

The design and development of a TUI architecture suitable for the support needed within higher education have been explored in parallel to the main contribution of this research. Through the construction and deployment of basic tabletop architectures (Luderschmidt, 2011; Schubert, 2016), practical experience and insight were gained on the various physical and technical limitations commonly encountered in the utilisation of tabletop architectures. Along with an identification of a research knowledge gap in the literature for guiding developers towards successfully deploying TUI frameworks (Sheridan *et al.*, 2009), the following subordinate research question was outlined;

> *Are TUI tabletop architectures suitable for use in higher educational institutes?*

This proposition has been investigated through an agile methodology in tandem with the challenges and difficulties encountered during TUI framework development. Whilst the empirical requirements in section 4.2.1 serve as the foundational design goals of the architecture, the applicability and effectiveness of each design iteration are investigated through an amalgamation with a contextual TUI framework. This approach provides a significant scope for participant interaction with the tabletop architecture and enables the assessment of the physical construction within a teaching and learning context.

To this end, a quantitative research methodology is adopted, in tandem to the quasi-experimental research design of the main contribution, to obtain quantifiable insight and feedback on the design efficacy of physical TUI architecture using a descriptive survey. This approach has been selected due to the lack of time constraints on participants and the flexibility in data collection

(De Vaus, 2013), which collectively aided the understanding of behavioural constructs on the usability and acceptance of the designed tabletop TUI setup in an HEI context.

3.3.2 Selection of Participants

This research is conducted within the Faculty of Science and Technology at Middlesex University, which provides access to a relatively large student population for participation within this study. Nonetheless, albeit having access to a broad population, the different programmes and courses offered within the faculty impart an uneven distribution of students towards specific computing science and technology concepts. To this end, the study adopts a non-random sampling process for participant selection.

More specifically, due to the specific nature of each complex and abstract concept represented within the proposed TUI frameworks, a purposive sampling strategy is undertaken. By means of this approach, participants are considered eligible and able to contribute towards the study based on exposure to pre-requisite knowledge that is covered within courses pertinent to the threshold concept addressed by each experimental framework respectively. To this end, participant sampling and selection is restricted to students who are enrolled in specific modules in which the threshold concept is introduced within their respective programme. This provides the study with a population size of 16 – 48 appropriate participants for each of the intervention method.

The constraints defined within this sampling strategy also favoured the overlaying of different data collection procedures utilised in answering the diverse subordinate questions. Thus, by ensuring that participants were purposively sampled according to their academic interest and need, helped to provide an unbiased evaluation methodology to determine the suitability of the physical tangible architecture being utilised as well as understand the behavioural intention of students to interact with the proposed educational technology.

Whilst no selective criteria within the purposive sampling strategy confines eligibility based on the participants' personal demographics, a number of population phenomena were observed from the available population sample. Due to the marketing and recruitment strategies undertaken at Middlesex University, students enrolled in undergraduate and postgraduate programmes commonly vary considerably in age and experience, since offerings are made for students to read their courses in either full-time or part-time mode. This implied that participants' age is commonly distributed between 17 up to 52 years, with a median age of 21 years old. This widespread distribution factor is further compounded by an uneven level of a priori knowledge between participants, which albeit enrolled within the same module and studying at the same academic level, potentially embody significantly different levels of experience and exposure towards their domain of study from different employment opportunities. Finally, analysing the admissions phenomena observed on the campuses gender-base also outlines a skewness in male distribution amongst the population sample, which is alas characteristical of enrolled students in science and technology programmes (Dečman, 2015; Fox, 2015).

3.3.3 Experimental Intervention and Materials

In line with the hypotheses explored within this study, the intervention methodology employed provides a resolution to the principal research question which investigates the effectiveness and suitability of TUI frameworks for teaching and learning abstract and complex concepts in HEIs. Thus, the experimental design alters the educational technology utilised in teaching and learning a respective threshold concept as the independent variable during a tuition session. The effect of this experimental intervention is subsequently quantified by assessing the dependent variable of knowledge gain and/or behavioural intention as detailed within the data collecting procedures described within section 3.3.5.

As illustrated within the overarching research approach depicted in Figure 3.1, the experimental intervention has been designed so as to provide a direct comparative assessment of the proposed TUI framework in respect to the use of a control educational technology for teaching and learning the same abstract and complex concept. This experimental intervention has been adopted for assessing both the effectiveness of TUI frameworks to aid teaching and learning as well as their suitability for deployment in HEIs, through the TAM4Edu acceptance model, in contrast to conventional educational technology.

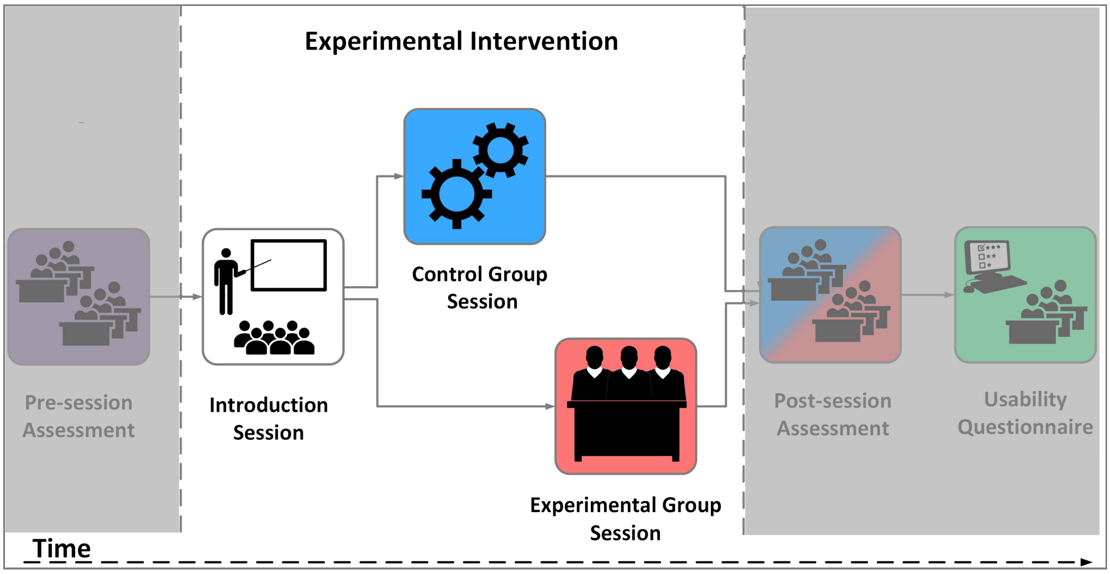


Figure 3.1 Experimental Intervention adopted to assess the effectiveness and suitability of proposed TUI frameworks within this research.

To ascertain an equal level of prerequisite knowledge needed within the subject amongst the whole participating student sample, a short introduction to the session scope is held at the start of the intervention for the entire class during which the provision of any pre-conceptual information is delivered collectively. Following this session, the entire cohort is randomly allocated into two quasi-equal groups for their distinct tuition sessions of the threshold concept being covered. This is practically conducted by dividing the class across a suitable split according to their seating position with the lecture hall, ensuring no bias of student selection is indirectly imparted.

The two student cohorts are accordingly allocated towards control and experimental sessions respectively, and alternatively sent on a short break or asked to attend their upcoming tuition session. According to the allocated group, each student cohort is subsequently asked to attend a distinct laboratory room for their session whereby the educational technology being assessed has been pre-setup and engaged with accordingly. Within each session, a common set of slides is preselected from the lecturing material which outlines the core concept in accordance with the module syllabus and these are intentionally delivered through repeated explanations and identical exemplifications.

Whilst the experimental intervention is maintained largely consistent throughout the study, the scope of each comparative intervention is varied according to the iterative evaluation methodology undertaken within this research. Thus, the educational technology used by the control groups, as elucidated in Table 3.1, is altered by making use of different educational technologies currently adopted within HEIs. As tabulated below, a direct comparison is thus undertaken against; traditional lecturing setups employing digital projectors and smartboard technology, conventional GUI based laboratory sessions deploying industry-based development platforms, gamified web-based educational software as well as an identical in-house WIMP interface software developed similarly to the respective TUI graphical interface.

Table 3.1: Overview of educational technologies used as experimental control in evaluation sessions

TUI Framework	Control Group Educational Technology
Computer Networks	Industry-based visual simulation environment
Database Normalisation	Digital data projector and active smartboard
Queuing Theory	Digital data projector and active smartboard
Multi-threaded Task Scheduling	Digital data projector and active smartboard
Search-Space Problems	Web-based gamified learning platform
Object-Oriented Programming	Industry-based integrated development environment
Artificial Neural Networks	In-house developed identical WIMP software
Robotic Operating System	Digital data projector and active smartboard

Throughout the course of answering the research question, a progressive experimental evolution is adopted on the intervening variables of tangible elements and interactive TUI designs. By innovating the design of these TUI elements, the research explores the capacity of TUI frameworks to be considered effective and suitable in teaching and learning conceptually different abstract notions encountered within computing science and technology disciplines. Whilst the above experimental intervention has been simultaneously adopted during the quasi-experimental methodology for answering the various quantitative subordinate questions, the materials employed in addressing specific hypothesis are described in further detail within their respective sections.

3.3.3.1 Educational TUI framework designs for HEI contexts.

In order to address the subordinate question on what are the effective interactive methods that can be employed within TUI frameworks, the development and experimentation with tangible elements have been increasingly refined throughout this research. Significant betterment has been obtained through the introduction of Playmobil® figurines as well as eventually the use of 3D printing technology, both of which expanded drastically the symbolic capabilities of tangible designs. Apart from providing a plethora of modelling possibilities, the design capacity of these technologies enabled the integration of active actuators, sensors and microcontrollers leading towards the innovative experimentation with active tangible elements.

From a programming perspective, as tabulated in Table 3.2, the initial TUI software development has been prototyped inside Processing.js environment and subsequently recoded in Java for functional reliability once validated. Whilst the integration of code libraries such as JavaFX and JSSC extended the capabilities of Java development, a scalability constraint was eventually encountered from both an integrational and graphical perspective. Although the adoption to Python served as an interim solution for embedding smart peripherals and active tangibles, the native graphical capabilities of the environment still posed a substantial burden on the development phase. To this end, the choice of a game development engine, Unity™, has been subsequently identified, which alleviated the programming efforts in graphical and animated representations whilst providing logical scalability through an integrated C# compiler.

Thus, a sequential experimental approach has been undertaken by means of the proposed TUI frameworks, whereby insight, experience and progress obtained from prior developments contributed towards the innovative investigation, development and proposition of progressively enhanced frameworks as highlighted in Table 3.2.

Table 3.2: Overview of principle TUI design element investigation

TUI Framework	TUI Design Element	Development Language	Interactive Design
Computer Networks	Tangible Interaction Design	Processing.js / Java	Proxemic Interaction
Database Normalisation	Tangible Interaction Design	Java	Audio Interaction
Queuing Theory	Tangible Interaction Design	Java	Symbolic / Collaborative Interaction
Multi-threaded Task Scheduling	Tangible Interaction Design	Java	Comparative Interaction
Search-Space Problems	Smart Tabletop peripherals	Unity	Gamified Learning / Interactive Placeholders
Object-Oriented Programming	Smart Tabletop peripherals	Java / Python	Interactive Platforms
Artificial Neural Networks	Active Tangible Interaction	Unity	Distributed Computing
Robotic Operating System	Active Tangible Interaction	Unity	Real-time Data Sensing

3.3.3.1 A TUI interactive tabletop architecture to support HEI contexts.

Based on the critical review on section 4.1 of the physical TUI models adopted within the literature, a tabletop architecture has been selected based on the form-factor affordances of this configuration. Hence, an initial tabletop prototype was set up which using rudimentary timber beams which provided a platform for design and experimental assessment of the initial TUI systems.

In view of the challenges and limitations encountered, an architectural review was undertaken together with a group of stakeholders; including academics and technical specialists, from which the requirements for an effective TUI architecture were established. These design criteria provided research focus for addressing the subordinate question on the suitability of adopting TUI tabletop setups within HEIs.

A design proposal was consequently designed on Computer-Aided Design (CAD) software, integrating the various experimental and heuristic improvements noted within previous TUI developments. Based on the designed digital model, a cardboard prototype was constructed to calibrate the physical design with the electronic components in the architecture. Further acumen on usability and accessibility constraints was also acquired from a small sample alpha-stage user testing on the cardboard mock-up. These design considerations ultimately guided the construction of interactive TUI tabletop architecture which was utilized to embed the subsequent TUI frameworks proposed within the core research contribution.

3.3.4 Instrumentation

The primary instrument provided to participating students during all the experimental evaluation sessions is a letter of ethical consent for participating in this research. The latter provided participants with information on the study's purpose, evaluation and data collection procedures, investigated findings, confidentiality, the type and duration of data retained, the voluntary nature of participation and an offer to answer questions. These statements were compiled in line with the ethical approval obtained by Middlesex University for the undertaking of this research. An additional copy of this instrument has been provided to students for personal records. Participants were asked to respond to the question that certifies they have read the letter of information and agree to participate in this survey by opting or otherwise to sign and date the consent provided form.

The research setting innately constrains the undertaking of experimental evaluations during specific instances within the academic term. Intrinsically, this led to the design and deployment of experimental instruments in tandem throughout the research. Nevertheless, albeit imparting a valuable influential effect on the exploratory study of subsequent research questions addressed along this research, the section details the instrument utilised to investigate each contribution in respective sections.

3.3.4.1 Educational TUI framework designs for HEI contexts.

> **Impact**: *What are the effective interactive methods that can be employed in TUI frameworks to aid in the teaching and learning of threshold concepts within computational science and technology subjects?*

In line with the pre-test/post-test research design implemented for this hypothesis, the instrument for eliciting knowledge capture through educational technologies is designed to measure this dependent variable prior to and after the experimental intervention. In line with similar literature in evaluating educational technologies, the use of written tests is adopted to assess the level of understanding of individuals in each instance (Catala *et al.*, 2011; Skulmowski *et al.*, 2016). As evidenced in Appendix B, a different pair of examination scripts were composed for each of the identified threshold concepts through the use of open-ended and/or multiple-choice questions (Lan, 2007). Based on this approach, to ensure a valid academic investigation within this research, each assessment strategy has been designed following a review of past examination and/or assignment questions utilised within the respective module. Together with the assistance of academic domain experts, each examination script is consequently designed to collectively elicit different aspects of conceptual knowledge proficiency including; procedural, theoretical, detail-focused and problem-based understanding.

So as to obtain a relatable and comparative assessment between both pre-test and post-test assessments and to mitigate the bias introduced from sequential exposure experienced by students towards questions and their wording, both assessments are designed to assess similar conceptual and practical knowledge on the session principles whilst presenting students with a different set of questions. Whilst the quantity and nature of questions varied according to the particular concept being assessed, each set of examination scripts totalled to an equal grade and marks have been allocated to each individual question in close liaison with the academic lecturer responsible for running the respective topic.

As shown in Appendix B, open-ended questions have been designed to provide students with the ability to enlist their answers directly below each question within the examination script. This is achieved through the use of empty writing lines for descriptive answers or through the use of an empty boxed space which allowed students to illustrate their solution graphically. A unipolar assessment strategy has been adopted for each question whereby through the design of a marking scheme by an expert academic in each respective domain. Thus, an incremental scale from 0 to the maximum allocated mark, is used to grade each answer. This provided the ability to fairly and consistently grade partially correct answers or methods as outlined in Appendix B.5.2.

Sections involving multiple-choice questions (MCQ)s have also been designed to allow students to select the desired answer from a provided list of alternatives directly on the examination script. Three to four possible answers are provided for each assessed question and an expert academic helped to ensure the absence of leading questions. Furthermore, the provided options are assessed for practicality and to avoid students to identify the correct answer using only a process of elimination. Whilst all close-ended questions are graded through a positive grading strategy, the summative mark attributed to each question is varied in accordance with advice by the domain's academic expert.

3.3.4.2 A TUI interactive tabletop architecture to support HEI contexts.

> **Normative:** Are TUI tabletop architectures suitable for use in higher educational institutes?

In the final section of post-test examinations delivered to students after their experimental intervention, a set of questions are used to elicit subjective feedback from students based on their experience with the respective educational technology used. These rating-scale questions are intentionally designed to enable participants to express their perceptions on the engaged technology using a labelled 7-point Likert scale. Thus, participants scored their attitude towards a set of five statements eliciting different aspects of their interaction experience;

- Perceived Usefulness (PU):
  Through the technology, I have learnt the subject effectively.
- Perceived Ease of Use (PEU):
  The used technology was rather difficult to operate.
- Perceived Enjoyment (PENJ):
  I had fun using the educational technology.
- Usability (USE):
  The feedback was intuitive.
- Perceived Lecture Attention (PLA):
  I felt very attentive during this lecture.

This strategy underlying this instrument section enabled to elicit formative feedback on the proposed TUI setup from users, which apart from guiding the iterative development and progress of TUI frameworks throughout this research, enabled the suitability investigation and agile refinement of the tabletop architecture. This instrument section also provided the foundational basis to the explorational research in developing a technology acceptance model for educational technologies, TAM4Edu.

3.3.4.3 Technology Acceptance Model for Educational Technology

Correlative: What factors influence the acceptance of TUI systems in higher education?

The design need for the TAM4Edu instrument stems from a critical literary analysis of the TAM model evolutions and the tangential studies in online-based education (Yuen and Ma, 2008; Teo, Ursavaş and Bahçekapili, 2012; Baturay, Gökçearslan and Ke, 2017). In line with the subordinate research question investigated through this study, a set of evaluation determinants are adapted within the proposed survey toward assessing factors influencing user acceptance of educational technology in HEIs.

The first-cycle instrument design is based on the amalgamation of TAM literature contributions and experiential knowledge obtained from reflective questions in the TUI framework evaluations (Compeau and Higgins, 1995; Venkatesh and Fred D Davis, 2000; Fleming and Baume, 2006; Venkatesh and Bala, 2008; Holden and Rada, 2011). Albeit the constructs are well supported in literature studies, an extensive set of determinant specific questions is uniquely adapted in the instrument design to reflect contextualization and potential correlative hypotheses pertinent to the educational domain.

As shown in Appendix C.1, the initial instrument is designed online through the Google Form platform and consisted of 44 questions representing different facets of the identified determinants in assessing the suitability and behavioural intention of using educational technology in HEIs. Participants score their reactions to each item, using a unipolar 7-point Likert scale, ranging from 1 *(strongly disagree)* to 7 *(strongly agree)* (Venkatesh *et al.*, 2003; Sundaravej, 2004). The questionnaire was spread over four sheets which students navigated using the "Next" button at the end of each page. In addition, the survey collected participants' demographic data such as; gender, age and enrolled year of programme study for moderation analysis, within a separate section of the questionnaire (Teo, 2016). Finally, the questionnaire presents two optional open-ended questions, whereby direct feedback is requested through comments on using the educational technology and assessment instrument respectively.

Based on the statistical analysis of the first-cycle development, the TAM4Edu instrument is subsequently refined to incorporate a subset of questions from the original design which invoke the most significant factor loading to their respective constructors. The experience and insight garnered on the practical aspects of suitability evaluation have also been taken advantage of within this methodology, and these contributed directly towards a number of design considerations in the size, format and composition of the TAM4Edu instrument. To this end, the survey has been redesigned to include 24 determinant questions. The phrasing of each question is adapted in consultation with academic practitioners and educational experts at Middlesex University and consequently ratified after the first-stage validation.

To further the appropriateness and reliability of reference scales in TAM models, a 5-point Likert scale ranging from 1 *(strongly disagree)* to 5 *(strongly agree)* is adopted within the revised instrument (Ahmad and Ahlan, 2015; Idris, Mat Sin and Ya, 2015). As illustrated in Appendix C.2, the online instrument is reformatted within a two-page design, with the construct question order randomised and specific items intentionally reverse coded. A moderating demographic data collection section is similarly retained within the proposed TAM4Edu instrument, whereby participants are asked for gender, age, year-of-study, feedback comments and educational technology engagement through the use of appropriate open-ended or multiple-choice classification options.

3.3.5 Procedures and Data Collection

Whilst the scope of the evaluation interventions undertaken on TUI frameworks and TAM4Edu models evolved throughout the various stages of this research, similarity has been retained in most of the experimental methodology adopted. Through the proposal of distinct TUI frameworks, the study aimed to evaluate the effectiveness and suitability of TUI within higher education through the data collection processes illustrated in Figure 3.2.

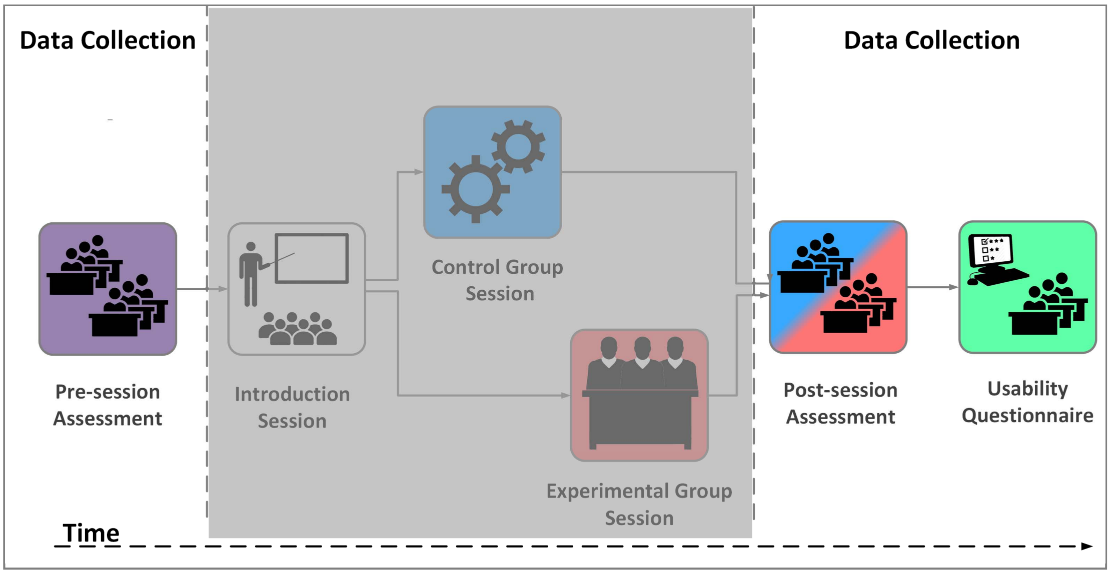


Figure 3.2 Data collection sessions adopted to assess the effectiveness and suitability of proposed TUI frameworks within this research.

Governed by the academic cycle at HEIs, the adopted data collection methodologies have been synchronised with the natural delivery schedules of threshold concepts in different course curricula respectively. This strategy provides the optimal approach for assessing the capacity and effectiveness of educational technologies to impact student knowledge since the relevant threshold concept, experimentally evaluated in each domain, is being delivered subsequent to the prerequisite knowledge covered within previous lectures. Furthermore, this approach curtails the amount of contextual information that would need to be introduced to students prior to engaging with the educational technology setups, thus retaining the knowledge capture aspect of the session focus solely on the controlled experimental environments.

To minimize the scheduling and participant attendance difficulties, evaluation sessions have been timed in tandem with the conventional 2-hour sessions commonly held within the University. In line with the ethical approval received from the university, prior to commencement of each data collection process, participants would optionally consent to volunteer within the study following a verbal and written briefing on the nature of the experiments and the data to be collected. Participating individuals would sequentially be randomly allocated between experimental and control groups in accordance with the experimental intervention design. Students who do not agree to participate within the study were not asked to undertake any data collection assessments and would attend their lecture with the control group in line with the conventional lecture plan that would be typically adopted for the module. Furthermore, so as to ensure that each student is provided with an equivalent opportunity to learn through the use of either educational technology, students selected within the control group have been offered the possibility to interact with the experimental TUI setup together with their lecturer following the research intervention.

Thus, as to ensure confidentiality and participant privacy, candidates have been explicitly asked not to include their personal details within any instrument. Conversely, each participant has been provided with a unique student number to mark his submission, which is randomly allocated based on the coincidental seating location of each student. This strategy provided the opportunity to compare pre-test and post-test scripts for each participant whilst anonymising the obtained results. Participating students are also notified that the grading of these assessments would not impart any impact on their module progress and that the collected data within this study would be analysed and stored collectively. Furthermore, students have been assured that feedback comments and scaled reactions in their subjective survey would remain confidential and analysed solely by the principal investigator to assess improvements in further development iterations of the experimental TUI architecture and/or frameworks.

3.3.5.1 Educational TUI framework designs for HEI contexts.

As illustrated within the comparative assessment strategy in Figure 3.2, two quasi-identical data collection procedures have been undertaken prior and after the experimental intervention, whereby student knowledge would be assessed through the use of a questionnaire instrument. So as to ascertain a fair and independent appraisal whilst providing a summative metric relational across all students these unseen tests were administered in the form of time-controlled assessments. To this end, students are granted a maximum of 15-minutes to answer the provided assessments, which are conducted collectively in a classroom setup under a closed-book exam condition.

Examination scripts from each evaluation session were subsequently marked by the appropriate academic lecturer of the subject through the design and use of a pre-compiled marking scheme. This provided the ability to maintain consistency between grading whilst also accounting for plausible and valid answers in open-ended design questions providing an equally fair academic judgement. Subsequently, results have been tabulated for visual and statistical analysis using appropriate software packages as described in section 3.3.7

To obtain a more holistic understanding of participants experience and involvement during experimental interventions, the inclusion of meta-data collection procedures have been additionally conducted during evaluation sessions. Through the assistance provided by collaborative researchers, who remained external to the experiment, the gathering of behavioural frequency counts has been obtained through observational methods assisted by the marking of telly marks on a designated data collection sheet (Kawulich, 2005; Weibel *et al.*, 2012). This methodology provides a quantitative measurement to gauge and enumerate the occurrence of collaborative interactions and engagements done by participants within their allocated group. Furthermore, through the design and integrational development of data collection strategies within the developed computational software, automated metadata capture procedures have been implemented through logged measurements on; experimental duration, interaction times, user engagement actions and system responses. This observational information is not designed to assess the knowledge gain and effectiveness of TUI setups for teaching and learning abstract concepts. Nevertheless, this metadata provides justification and insight towards the interpretation of the captured and analysed results.

3.3.5.2 Technology Acceptance Model for Educational Technology

The TAM4Edu instrument was administered to participants in tandem with the experimental interventions using either TUI frameworks or the control educational technology as illustrated in Figure 3.2. A similar data collection procedure has been retained throughout the adaptation of the assessment questions and construct model of the proposed instrument; whereby volunteering participants were asked to answer their questions online. Albeit the instrument design is optimised for effective data collection in format and consistency, a maximum of 20 minutes was still provided to participants to answer the provided question.

A set of laboratory computers were preloaded with the questionnaire webpage and participation was supervised by an academic/technical member of staff. The latter ensured students do not cross-contaminate their results through collusion as well as aided participants in ensuring their results are successfully uploaded at the end of the survey. Subsequently, the Google Forms platform was utilised to download the original responses by participants in comma-separated-value (CSV) which could be further tabulated through the use of data-handling and statistical analysis software.

The procedural application of the TAM4edu instrument in combination with the experimental interventions on both TUI and conventional PC-based educational technologies provides the opportunity to collect suitability data across different modality setups. This range of independent variables provides a holistic dataset to model and understand dominant factors in determining user behaviour in educational technology. Furthermore, the iterative data collection sessions provide a comparative dataset to evaluate the suitability of the proposed TUI frameworks with respect to a range of educational technology designed for experimental control.

To this extent, a first-cycle pilot study has been designed to aid to evaluate the validity of the correlative factor hypotheses described within the TAM4Edu instrument. Subsequently, the data collected within evaluations procedure during the second academic year provided a systematic and structured analysis on the perceived determinants of the model, allowing a statistical comparison to be undertaken on the suitability factors of TUI frameworks in HEI with respect to currently adopted technology.

3.3.6 Validity and Reliability

The quantitative validity of the research design within the study is intrinsically established on the premise that observed changes within the dependent variables are reflective of the effects generated by the use different educational technologies through the intervening variables of tangible elements and interactive TUI design (Gray, 2014). To this extent, a number of considerations have been made in the intervention and instrument design to reduce the potential impact from extraneous variables on the internal validity of the experimental methodology.

The sampling bias through extraneous experimental variables in the adopted quasi-experimental methodology is curtailed through the constrains implemented within the participant selection strategy. By means of the adopted purposive sampling, the research methodology ensured the educational delivery is of direct relevance to the sampled participants. This aided to support the investigated hypothesis by reducing bias in knowledge gain measurements from uninterested participants on the domain. Moreover, this approach also provided a more relevant representation for student behaviour intention in technology acceptance, directly elicited from the principle determinant of *Perceived Usefulness*.

Similarly, efforts were undertaken to account for the uneven experience and abilities of eligible participants, whereby through the use of a pre-test assessment, an individual baseline could be established to account for the knowledge base of each student prior to the experimental intervention. The potential maturation and memory bias introduced by this repetitive data collection procedure has been lessened through the development of a paired unseen assessment instrument for post-test which whilst eliciting similar conceptual knowledge, ensured a lack of sensitivity bias to already experienced questions.

Whilst these strategies alleviate the effects of extraneous variables, other variables such as students' aptitude and motivation to study as well as differential demographics in the selected sample can still pose a threat to the experimental validity. Whilst unable to directly subdue these concerns, these effects where intentionally dispersed through the random allocation of participants to experimental and control groups as well as through the innate anonymisation of assessment results. This approached aimed to reduce any grouping bias imparted by participating peers or assisting academic colleagues which could be based on apriori familiarisation with the participants' skills and behaviour.

As an attempt to curtail lecturing bias during the experimental intervention, the collaboration of academic members of staff has been sought for each experiment in line with their respective academic domain of expertise and responsibility within the university. Furthermore, the same lecturing academic is asked to deliver both sessions in a pre-agreed timeframe according to the exigencies of the concept. Efforts were also undertaken to reduce any discrepancies between the two sessions from a lecturing perspective. Thus, a unique preselected set of slides for lecturing the core concept were adopted during both sessions so as to constrain the explanation delivery and use of exemplification scenarios. These measures aimed to reduce extraneous discrepancies within the intervention sessions, aiming to provide a quasi-identical academic experience to participants and thus focusing the experimental validity on the investigated independent variable.

Considerations of construct validity have also been taken in the reliability and validation of the TAM4Edu instrumentation designed within this research methodology. The content development and design of each instrument in section 3.3.4 , is based on the adoption of well-cited research regarding the use and suitability of each construct. Furthermore, an academic expert review has been sought throughout the development of each instrument to ensure the validity and reliability of questionnaires to elicit the intended knowledge or reactive measurement from participants. To ensure reliable responses, deliberate measures are also undertaken in the instrument's design, through randomisation of the construct questions order and the use of reverse coded questions within the questionnaire. These measures aim to expose potential bias resulting from unengaged user responses within data pre-processing stages.

The iterative and agile methodology adopted within this research also provides the ability to undertake pilot studies on the proposed designs to optimise and ascertain their validity. To this end, assessment instruments underwent continual alterations throughout this research, taking into consideration statistical and internal reliability metrics from analysed former results and pilot/beta testing to guide in refining the appropriateness of the developed instruments and data collection procedures accordingly.

Apart from considering the internal validity of the quantitative research methodology, the external validity of obtained results has been ensured through the repetitive evaluations conducted. A direct demonstration approach is undertaken throughout this research to ensure the acquired data is not only relevant to a particular concept or setup being evaluated. Thus, by altering the abstract and complex concept in each intervention, spreading the research scope to different groups of students, varying the interaction models adopted within the TUI setups, the study aimed to lessen the intrinsic effects of these variables and thus aid in the generalisability of results. Furthermore, the diverse educational technologies deployed in the control group within help to dilute the effect caused the by innovative aspects of the experimental material investigated. Thus, the conducted interventions directly contrast the proposed TUI frameworks to alternatives such as; gamified software which provide a similar unfamiliar and enjoyable learning platform, industry-based graphical software which present a coherent evaluation from a computer-based simulation perspective, as well as a custom-developed WIMP interface software using identical animations and digital information throughout the experiment, providing solely a different interactive engagement opportunity to participants.

To this extent, this reproducibility of results sought to establish a significant confidence level in the observed data in knowledge gain and behavioural intention for contextually similar groups engaged with adopting TUI frameworks in HEIs. Moreover, the undertaken interventions collectively provide a systematic assessment of the effectiveness and suitability of the proposed TUI frameworks in relation to the different educational approaches adopted within HEI pedagogies. Thus, the study strives to answer the principal research question through proof by contradiction in relation to external effects which might impart bias towards the quasi-experimental methodology.

3.3.7 Data Analysis

The data collected within this quantitative research methodology is analysed to ascertain the significance and effectiveness through the Statistical software Package for Social Sciences (SPSS), which provided the ability to effectively test and interpret the extracted information in relation to the subordinate research hypothesis being investigated. The statistical methods undertaken on the data have been selected through an analysis of research in both statistics and assessment methodologies adopted in education. Furthermore, validation of the proposed analysis methodology has been sought from a statistician and academic expert at Middlesex University, who provided guidance and assistance towards ensuring correct analysis and interpretation of the evaluation data. The methodology applied to each subordinate hypothesis relates intrinsically to the nature of the investigative data collected within this study, and thus the respective analysis technique is described correspondingly in the subsequent sections.

3.3.7.1 Educational TUI framework designs for HEI contexts.

> **Impact**: *What are the effective interactive methods that can be employed in TUI frameworks to aid in the teaching and learning of threshold concepts within computational science and technology subjects?*

To validate the randomness of the participant group division prior to analysing and interpreting the obtained results, an independent-samples t-test analysis is conducted on the pre-test performance of each cohort to ensure no significant a priori knowledge discrepancy is present between experimental groups.

In accordance with the analytical techniques adopted in the literature to assess effective knowledge integration in educational participants, a differential analysis is adopted to infer the knowledge gain imparted through the respective educational technology (Hay, Kinchin and Lygo-Baker, 2008; Catala *et al.*, 2011; Skulmowski *et al.*, 2016). This dependent variable is measured as the resultant of the final acquired knowledge in relation to the a priori knowledge held before the intervention (Novak, 2010; Jarvis, 2014). Consequently, within this research methodology, the ordinal dataset obtained from grading students' assessments is tagged with unique participant identifiers to provide an individualistic correlative analysis ability. This approach enables a paired-sample t-test to be applied to the evaluation data which compares the mean results obtained by each participant to assess for statistical evidence of the difference between pre-test and post-test appraisals. This analysis provides an evaluation of the ability of the undertaken experimental setups to impart a level of knowledge gain on the introduced concepts validating the subordinate research hypothesis.

Finally, another independent-sample t-test is conducted on the means knowledge gain acquired by each experimental cohort to assess at a threshold statistical significance of $\rho < 0.05$, the comparative effectiveness of educational technologies. This analysis provides an interpretive metric on the effectiveness of the TUI interactive methods to aid in the teaching and learning of abstract and complex concepts with respect to current technology adopted in HEIs.

3.3.7.2 A TUI interactive tabletop architecture to support HEI contexts.

Normative: Are TUI tabletop architectures suitable for use in higher educational institutes?

The feedback responses about student perceptions derived after engaging with educational technologies were separately tabulated for each question. Based on the comparative nature of the experimental intervention, the obtained scores on the proposed interactive TUI architecture were segregated from those pertaining to interactions with PC-based control technology. Subsequently, a descriptive statistics analysis was performed on the ordinal data at a statistical significance threshold of $\rho < 0.05$, which enabled the collective analysis of user feedback.

These comparative results were further analysed in tandem with the objective time measurements recorded for each experimental intervention and the informal feedback provided from the lecturer delivering both sessions. Collectively, this feedback provided an understanding of the architectural suitability of TUI tabletops to engage higher education students with respect to conventual technologies deployed in HEIs.

3.3.7.3 Technology Acceptance Model for Educational Technology

Correlative: What factors influence the acceptance of TUI systems in higher education?

Prior to analysing the TAM4Edu data, a pre-processing methodology is adopted to screen for unengaged or unreliable data within the collected dataset. The nominal responses acquired for socio-demographic moderating factors are categorically enumerated, hence reducing the potential for erroneous data and assist the collective analysis process. No exclusions are performed based on the participant outliers' responses since all acquired ordinal responses provided equal relevance to the model.

Instances of missing data are however checked for their Missing at Random (MAR) characteristic and appropriately imputed or omitted accordingly. A pre-processing analysis is also undertaken on the reverse-coded questions, whereby participants responses were assessed for reliability. This supports the identification of unengaged responders by assessing a suitable degree of variance in their answer set ($\sigma < 0.5$) and hence ensure no bias is imparted in the model analysis from invariant responses on constructs (Lowry and Gaskin, 2014).

Descriptive statistics are subsequently analysed for each construct, reporting the mean and standard deviation of respondents in relation to their education technology intervention (Teo, 2016). Frequency analysis is also conducted on the dataset to assess the skewness and kurtosis effects on the obtained dataset (Kline, 2011). Furthermore, a Kaiser-Meyer-Olkin (KMO) test is undertaken on the model's data to ensure the dataset is adequate for factor analysis sampling (Williams, Onsman and Brown, 1996). Consequent to these results, the TAM4Edu dataset is segmented in accordance with the determinant constructs and labelled accordingly for subsequent analysis.

The initial dataset acquired on the first-cycle pilot study of the TAM4Edu model was used to evaluate the validity of the model's hypotheses on influencing factors. To this end, a Cronbach's reliability analysis was conducted to assess the inter-item reliability of each distinct factor. An exploratory factor analysis was further conducted on the loading coefficients of survey questions for each determinant, which provided a statistical design optimisation of the TAM4Edu instrument through the derivation of a representative subset of questions. Subsequently, factors have been analysed using a bivariate Pearson correlation to identify and quantify the inter-factor functional dependencies and validate the instrument's correlational hypotheses on factors impacting educational technology acceptance.

The research hypothesis on the suitability of TUI frameworks within HEI was addressed through the analysis of the second-cycle data collection. The comparative methodology within the intervention design enabled the results to differentiate students' perceived differences in the adoption and use of TUI technology with respect to conventional PC based software. Thus, the segregated data is analysed against type 1 analysis error using a one-way multivariate analysis of variance (MANOVA), which through a Pillal's Trace test ensured robustness towards potential inequalities in determinants covariance matrix stemming from the finite sample size (Cramer and Bock, 1966). Finally, a series of ANOVA tests are undertaken on the independent determinants, enabling the analysis of statistically significant factors that influence the suitability of TUI frameworks in the adopted HEI context.

3.4 Qualitative Research Methodology

Whilst the core contributions of this study have been investigated through a post-positivist quantitative research methodology as detailed in section 3.3, a different paradigm is adopted to understand the observed phenomena in the teaching and learning of abstract and complex concepts. The investigation of this research question is subsequently conducted in chapter 7.

3.4.1 Research Design

Albeit the pedagogical notion of *'Threshold Concepts'*, proposed by Meyer and Land (2003, 2005, 2006; 2008) posits a set of distinctive difficulties encountered in teaching and learning abstract concepts (Perkins, 1999; Tight, 2014; McCredden *et al.*, 2016), consensus in pedagogical literature outlines that each abstract and complex presents a set of specific and peculiar characteristics uniquely pertinent to each concept (Azevedo *et al.*, 2011; Borghi *et al.*, 2017; Hayes and Kraemer, 2017). To this end, a qualitative research methodology is adopted in this research, whereby through an interpretivist paradigm, a set of relatable factors is sought across each conceptual investigation undertaken within the domain of computational science and technology.

Based on the premise that each threshold concept is embedded in mental processes or emotions that specify relevant situational aspects (Wiemer-Hastings and Xu, 2005), a relativism ontological position is considered within this approach, which seeks to understand the subjective perception of each concept by individual participants (Agostinho, 2005). To support this methodology, a combined emic-etic epistemology orientation is adopted, which through the direct interaction with participants, is able to elicit their subjective knowledge and individual perspectives, and subsequently compare and assess the obtained variables for their generalisability (Berry, 1990; Jingfeng, 2011; Guzmán-Valenzuela, 2016).

To this extent, the research design adopts an in-depth interview methodology with the sampled participants which aims to explore the individual experiences and perceptions in rich detail (Guest, Namey and Mitchell, 2013). This design was favoured as opposed to a focus group approach since it provided an unbiased and confidential understanding of the participant's knowledge through a one-to-one setting, whilst facilitating the logistical setup of data collection (Adams and Cox, 2008). Furthermore, this research design provided the ability to discuss and probe further detail about the nature of the abstract concept being investigated, which is inherently difficult to contextualise due to the tacit nature of the conceptual understanding.

3.4.2 Selection of Participants

Exploiting the contextual environment of this research at Middlesex University, as detailed in section 3.1, the research study had opportunistic access to academic members of staff within the Faculty of Science and Technology based in both the Malta and London campuses. Whilst this setting provided potential access to over 140 academics, the specific nature of the adopted qualitative research methodology constrained the selection of participants through the identification of *"key informants"* (Guest, Namey and Mitchell, 2013). This purposive sampling entailed the selection of participants based on specific criteria in relation to their domain of research expertise, courses and topics led within programmes, as well as their level of experience in lecturing a specific subject. To this extent, a subset of eligible participants is selected across both Middlesex University campuses which hold respective expertise on either of the identified complex and abstract threshold concepts within this study. This led to the recruitment of 19 academics, with an identification of two to four key informants for each threshold concept.

Selected participants are contacted via email on their official institution email address, through a first email which introduces the study, requests their participation, explains why they have been selected and outlines the voluntary and confidential nature of the study. The email also requests the scheduling of a one-hour meeting in person or via video conference (using Skype™) at the participant's discretion and convenience, and thus included the researcher's contact information and an attached ethical consent form. A second and final email is sent to non-respondents two weeks after the initial correspondence, kindly reminding participants of the study and once again requesting their participation. The emails sent are appropriately timed to align with the academic recess period of the University, and thus aimed at facilitating the availability of willing participants to this study.

3.4.3 Instrumentation

The conduct of the in-depth interviews was done in line with a precompiled interview guide as shown in Appendix D.1. In accordance with the research design methodology, this framework was designed so as to provide a list of open and non-directive questions to participants enticing an exploratory understanding of their experience and perceptions. Albeit the structure of questions was compiled sequentially, the scope and use of this instrument was to facilitate the conversation to converging with the research scope, whilst allowing for the pursue of emergent detail from participants.

Thus, a variety of questions were enlisted which provided a progressive in-depth review of the participants' knowledge and experience with understanding and teaching the identified threshold concepts. Moreover, the questions aimed to elicit a description of the abstract and complex characteristics of the discussed concept, together with an experiential overview of approaches and techniques commonly adopted by the participant to mitigate the encountered difficulties.

In tandem with the interview guide, the instrument also made use from a set of interview probes (Patton, 2002), which could be utilised at the discretion of the interviewer to help participants understand the intent of the question, elicit further information about a provided answer or seek clarification from the respondent. A notebook is also utilised as a part of the interview instrument, providing a way to record descriptions provided by the participants as well as annotate any comment accordingly.

3.4.4 Procedures and Data Collection

The interview process commences with a short narrative from the researcher about the scope of the research being undertaken together with an overview of how the research design will be conducted. Participants are informed on the type of information that will be inscribed on the notebook during the interview as well as an overview of the confidentiality and privacy policies in which data will be captured, stored and processed within this research. This approach provided reassurance to the ethical consent provided by the participant whilst intrinsically helping the interviewee feel comfortable with the interview procedure and the scope of the collected data.

Subsequently, the in-depth interview is conducted with the participant within the remaining duration of the meeting whereby through casual conversation, the instrument questions are progressively asked whilst providing the participant with the opportunity to explore and extend the provided answers through tacit knowledge elicitation. Throughout the interview, responses are written down in front of the participant, allowing for the possibility to retract or elaborate on comments through annotations. Finally, the recorded information is read back to the participant at the end of the interview to ensure that no errors, omissions or misunderstandings were documented.

The same in-depth interview procedure was repeated on all the volunteering participants within the study, providing an overlapping representation of academic experts for each of the identified threshold concepts within this research. Based on the constrained criteria for eligibility of participants, all responses are given equal weight, irrespective of seniority or power differentials between participants. This approach allowed for the ability to capture the different perspectives and experiences held by several academics on each subject, providing a more comprehensive understanding of the characteristics and difficulties encountered when teaching and learning each threshold concept to different classes and student demographics.

Following the analysis and mapping of the collected data to the developed categories, participants are further contacted for a secondary brief in-depth interview, whereby the respondent's answers and the corresponding descriptor mapping are discussed. During this interview, participants are informed about the data analysis that was undertaken on their primary answers and are consequently asked to review the validity and reliability of the undertaken mapping to their original information. Participants were invited to evaluate and discuss their original statements and any suggested alterations are recorded and recoded appropriately. This methodology provided a peer-review to the decontextualized categories, as well as a trustworthy representation of the participants' knowledge.

3.4.5 Data Analysis

The data analysis strategy employed within this methodology aims to derive a set of conceptual descriptors from the underlying patterns of the collected data. To this end, the data from participants were initially organised according to the threshold concept being investigated. The participants' responses are meticulously combed through using a coding methodology whereby observations and phenomena in relation to each concept are identified.

The raw codes outlined from each participant are subsequently collectively analysed and combined into categories which aim to decontextualize the information from the specific relation and lexicon of each concept. These categories are finally abstracted and labelled in relation to the conceptual phenomenon they describe. This process was iterated until a set of distinct categories outlined a list of relatable factors that could represent the nature and characteristics of complex and abstract concepts across each conceptual domain studied in computational science and technology.

The analytical coding and mapping processes are undertaken for each participant's data and are afterwards organised and presented back to the respective academic expert for review. This methodology validated the trustworthiness of the derived conceptual descriptors whilst ensuring that the data analysis and manipulation process was unbiased. Following any alterations and/or confirmations recommended by participants within the second data collection process, the individual responses to each threshold concept are amassed and analysed. An aggregate classification is consequently performed on the dataset of each threshold concept, whereby individual opinions are triangulated and classified according to a three-value metric. This approach provided the ability to differentiate between; occurrences of unanimous agreement on the applicability of a descriptor, occurrences of unanimous disagreement of the descriptor applicability, and instances in which participants provided conflicting but equally plausible conclusions to the descriptor's applicability to describe the threshold concept.

The agglomerated analysis on the qualitative data provides a set of descriptors which could be utilised to address the subordinate research question:

> **Correlative:** How does the design of tangible elements aid in the teaching and learning pedagogy of abstract and complex concepts?

A reflective analysis is subsequently carried out of the design considerations integrated within the experimental TUI frameworks developed in this research. This analysis systematically yielded a set of empirically evaluated guidelines on the adoption and suitability of TUI design elements to address the pedagogical difficulties experienced in dealing with abstract and complex concepts in HEIs.

3.5 Role of the Researcher

The research methodologies outlined within the previous sections require the researcher’s primary role to safeguard participants and their collected data within the study (Sutton and Austin, 2015). Within the quantitative methodology undertaken, experimental interventions were designed so that participants can act independently of the researcher and replicate the same results, theoretically rendering the researcher’s role non-existent (Simon, 2011). A similar external approach was aimed for within the qualitative research methodology, whereby a pre-determined list of questions framed the intervention to ensure each of the participants experienced a consistent interview design (Patton, 1990; Austin and Sutton, 2014).

Nevertheless, the undertaking of research activities within an educational context is inherently an interactive process and thus the researcher is bound to interrelate with participants (Seroka, 1999). Moreover, post-modern theories in qualitative research postulate that the researcher is seen as an intrinsic part of the research methodology and plays a fundamental role as an instrument of data collection and interpretation (Denzin and Lincoln, 2008; Tufford and Newman, 2012; Creswell, 2014). Further studies outline that as the researcher becomes immersed in the phenomenon of interest, his/her outlook, thoughts, life experiences and observations have a high likelihood of influencing the research process (Gee, 2011), and thus the researcher’s bias should be made transparent (Parker, 1994).

To this extent, a potential area of bias within this study is the fact that the researcher is an academic member of staff within the Faculty of Science and Technology at Middlesex University where the study took place. This background facilitates the execution of the research methodology due to the contextual knowledge of the research setting, the availability to synchronise experimental interventions, and potentially the ability to recruit participants for the investigated research questions. However, while the researcher acknowledges that this conflict of interest led to the ability to identify with participants, an explicit effort was undertaken to ensure the researcher's values, views and opinions are not imposed on participants during the experimental interventions, interviews and data collection procedures conducted. Thus, the focus of each research method was to explicitly designed to explore, elicit and understand the investigated phenomenon from the participants perspective with an open mind (Babbie and Mouton, 2001).

As outlined by Brannick and Coghlan (2007), the researchers' insider outlook presents a valid and useful method of providing important knowledge on the context that is often overlooked by outsiders. In addition, based on the personal researcher's motivation outlined in section 1.1, the undertaking of this study provided the reflexivity opportunity to research an in-depth understanding of the TUI frameworks under investigation (Burns, 2006). As an academic member of staff, the effort conducted within this study contributed both to the researcher's professional progression as well as to invoke the exploration of tangible user interfaces in higher education. Acknowledging that research neutrality is impacted by the subjectivity of the investigator, the outlined affiliation helps to signify the researcher's disposition to the findings and contributions within this study (Luttrell, 2010; Denzin and Lincoln, 2017).

Chapter 4
Designing a Tabletop Tangible User Interface Architecture for Higher Education

To address the limitations outlined in chapter 2 for the adoption of TUI in HEI contexts, the study set to design and develop a TUI architecture aimed to address the peculiar requirements of this domain. Following a structured critique in section 4.1 on the various TUI architectures proposed in the literature, the dissertation set out to elicit the peculiar requirements of HEI adoption in section 4.2.1. Design and implementation considerations are subsequently described in section 4.2 together with innovative TUI peripherals to aid in the interactive teaching and learning of abstract and complex concepts. An evaluation on the suitability and efficacy of the proposed architectural design together with a discussion on the obtained results is finally described within section 4.3.

4.1 Architectural Frameworks

The ability to provide a physical interpretation to digital information has been exploited using various architectures for constructing TUIs. This section provides a brief overview of the main genres of promising architectural frameworks employed within the literature combining the classification criteria defined by Ulmer (2002) and Ishii (2006).

4.1.1 Kinetic Memory

Tangible Interaction activities were pioneered in kinetic memory architectures which blur the boundary between physical and digital by amalgamating it's I/O. These devices use force-feedback actuation technology to allow the recording and playback of kinaesthetic gestures and movements as educational toys (Ishii, 2009). By allowing children to manipulate these devices whilst playing with them, these TUI systems memorise the intricacies of the original movement and repeat the gestures indefinitely using their robotic components. These gestures allow the physical space to illuminate the symmetric mathematical relationships in kinetic motions which have been adopted in primary education to teach children basic geometry, dynamic structures, and storytelling concepts. By providing students with the ability to experiment, play and self-express, these TUI systems provide the ability to discover and explore natural relationships in symmetry and dynamic motion.

By drawing closely to children's institution about their physical actions, toy examples such as *Curlybot* (Frei *et al.*, 2000) and *Topobo* (Raffle, Parkes and Ishii, 2004), shown in Figure 4.1 exploit body syntonic learning pedagogies (Papert, 1983) to distil ideals relating to gestures and form to physics, dynamic movement and storytelling. Whilst a similar *Programmable Bits* (Resnick *et al.*, 1996) concept was successfully released and commercialized later by *LEGO™* playsets (Weinberg and Yu, 2003), these TUI architectures differed mainly in not requiring any reading or creation of software programmes. Thus, the reliance on physical manipulation brought this computing technology accessible to even younger children (Ishii, 2006). Recently, this TUI architecture was also commercialised in the *Cozmo* robot, which embedded artificial intelligence to interact with users via audio and motion patterns in a similar fashion.

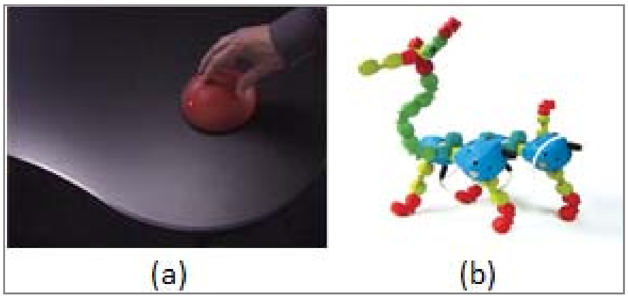


Figure 4.1: Examples of Kinetic Motion architectures used as educational technologies:
a) Curlybot (Frei et al., 2000),
b) Topobot (Raffle, Parkes and Ishii, 2004).

Whilst the initial deployment of these systems made innovation impact, their adoption in educational contexts has been limited to basic concepts. From a scalability aspect, kinetic motion architectures require the procurement of individualised units, which due to their electronic complexity often provide expenditure burden on institutions. The limited interaction and motion capabilities further limit the technology to playful operation, hence constraining the TUI's system implementation to primary education.

4.1.2 Constructive Assembly

The introduction of dedicated microprocessor-based components within these artefacts led to TUI architectures to progress within the domain of constructive assemblies. Building upon the interconnection of modular physical elements, the domain allows users to interact with the physical fit between objects and their unique kinetic capabilities to construct larger architectures with varieties of movement (Ishii, 2006). This domain of TUI systems, initiated by intelligent modelling kits such as *Universal Constructor* (Frazer, 1995) saw implementation in primary education in examples like *AlgoBlock* (Suzuki and Kato, 1993), *Story Beads* (Barry, 2000), *Triangles* (Gorbet, Orth and Ishii, 1998), *Blocks* (Anderson *et al.*, 2000), *GDP* (Anagnostou, Dewey and Patera, 1989), *StoryMat* (Ryokai and Cassell, 1999), *ActiveCube* (Kitamura, Itoh and Kishino, 2001) and *System Blocks* (Zuckerman and Resnick, 2004).

By allowing users to create computational expressions in the form of attaching blocks in a sequential pattern, these TUI systems enable a continuous interaction design to provide a persistent connection between a physical object interaction and digital information (Shaer, Horn and Jacob, 2009). Moreover, the tangible aspect allows user's to undertake several interactive actions in parallel, heightening the learning experience provided (Ullmer and Anders, 2002). More advanced constructive architectures such as *Navigational Blocks* (Camarata *et al.*, 2002), *Thinking Badges* (Borovoy *et al.*, 1996)*, TSU.MI.KI.* (Itoh *et al.*, 2004) and *Learning Cube* (Terrenghi *et al.*, 2005), exemplified in Figure 4.2, used digital feedback to enhance student's knowledge and skills in mathematics, history, robotics and language translation. Furthermore, commercialised constructive assembly kits such as *Lego Mindstorms*™ (Resnick *et al.*, 1996) further introduced logical problem solving and robotics concepts to younger audiences (Bers and Portsmore, 2005).

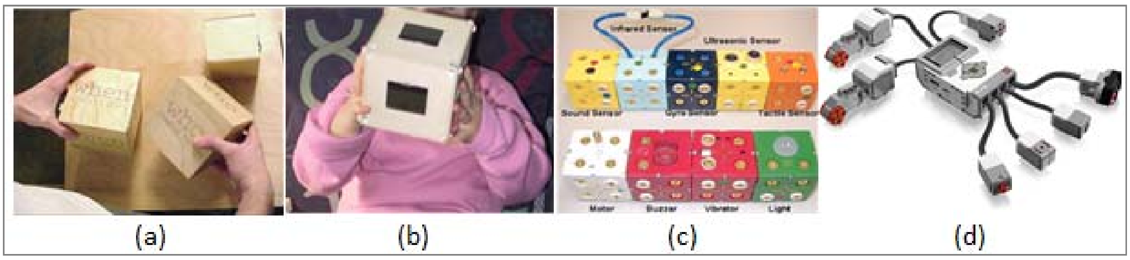


Figure 4.2: Constructive architecture examples:
a) Navigational Blocks (Camarata et al., 2002),
b) Learning Cube (Terrenghi et al., 2006),
c) TSU.MI.KI (Itoh et al., 2004),
d) Lego Mindstorms™ (Resnick et al., 1996).

Whilst these architectural frameworks allowed for the customisation of their digital content, their physical structures are quite specific and I/O components usually small in size. This implies that albeit being relatively cheap to procure, only one student can interact and visualise the data on each TUI system. Thus, commonly results in a scalability burden to utilise these technologies within an educational classroom environment.

4.1.3 Tokens and Constraints

Another facet of TUI systems interlinked the physical and digital worlds using a token and constraint (TAC) approach. This was pioneered in the *Marble Answering Machine* (Crampton-Smith, 1995) concept which albeit never being implemented further from than a prototype model, served as an influential design to more popular TAC setups such as *DataTile* (Rekimoto, Ullmer and Oba, 2001), *mediaBlocks* (Ullmer, Ishii and Glas, 1998), *LogJam* (Cohen *et al.*, 1999), *Tangible Query Interface* (Ullmer, Ishii and Jacob, 2003), pictured in Figure 4.3.

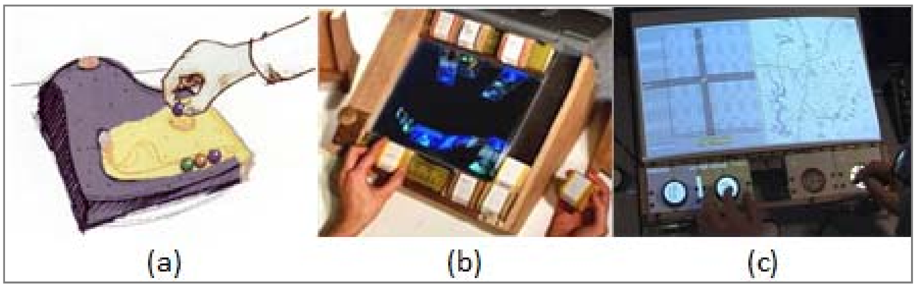


Figure 4.3: Token and Constraints architecture examples:
a) Marble Answering Machine (Crampton-Smith, 1995),
b) mediaBlocks (Ullmer, Ishii and Glas, 1998)
c)Tangible Query Interface (Ullmer, Ishii and Jacob, 2003).

Within this architecture, Tokens are discrete, spatially reconfigurable physical objects that are dynamically bound to digital information or operations. Constraints, on the other hand, are complementary confining regions within which tokens can be placed (Shaer and Jacob, 2009). The latter are often embodied as physical structures that mechanically channel how tokens can be manipulated and hence define the digital mapping of operations and properties that tokens trigger in their confines (Ullmer, Ishii and Jacob, 2005). Within the educational domain, these TUI systems engage the spatial perception of users to manipulate the digital information presented. Employed in contexts of multimedia representation (Ullmer, Ishii and Glas, 1998) and database querying (Ullmer, Ishii and Jacob, 2003), students were allowed to experiment and learn the effects of shuffling the sequential execution of the associated digital content.

Whilst providing instrumental designs for an innovative approach to embodying digital information in TUI architectures, TAC systems are highly context specific and require major hardware and software redesign for application in different contexts. Moreover, the limited interaction area of constraints makes collaborative learning difficult to achieve, hence curbing the effectiveness in classroom setups.

4.1.4 Workbench

The adoption of TUI architectures for multi-user collaborative interaction was introduced via the design workbench setups which employed horizontal interactive surfaces within its architecture. Projects like *AudioPad* (Patten, Recht and Ishii, 2002) and *IP Network Design Workbench* (Kobayashi *et al.*, 2003a) based on the *Sensetable* (Patten *et al.*, 2001) workbench architecture use electromagnetically tagged objects on a tabletop surface which are tracked using a matrix array of antenna elements as shown in Figure 4.4(a). Analogous architectures were proposed by the *musicBottles* (Ishii, Mazalek and Lee, 2001) and *TangiSense* (Kubicki, Lepreux and Kolski, 2012) architectures which employed a RFID transceiver array to track tagged objects whilst providing illuminative feedback by either overhead projection or an RGB LED matrix as shown in Figure 4.4(b). These projects saw deployment in both commercial aspects such as network performance simulation (Kobayashi *et al.*, 2003a) and digital audio processing (Patten, Recht and Ishii, 2002) to educating primary school children on story narratives (Mazalek, Wood and Ishii, 2001) and colours (Kubicki *et al.*, 2015). Within these contexts, the collaborative and interactive abilities registered significant advantages in engaging non-expert users on the simulated tasks (Ishii, 2006).

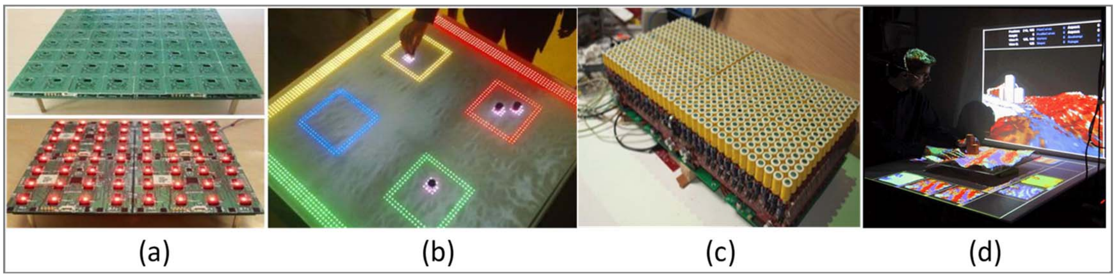


Figure 4.4: Workbench architecture examples:
a) Sensetable electromagnetic array (Patten et al., 2001),
b) TangiSense RBG LED illumination surface (Kubicki, Lepreux and Kolski, 2012),
c) PICO magnetic matrix (Patten and Ishii, 2007),
d) Sandscape interactive workbench (Ishii et al., 2004)

The coupling of physical tangible manifestations with the digital information was further strengthened by the *Actuated Workbench* (Pangaro, Maynes-Aminzade and Ishii, 2003) and *PICO* (Patten and Ishii, 2007) architectures which used magnetic matrices, shown in Figure 4.4(c), to interactively control the position of physical tangibles. These projects provided bi-directional physical interaction whilst enhancing the user's ability to understand physics concepts such as magnetic attraction and repulsion (Pangaro, Maynes-Aminzade and Ishii, 2003) or even optimisation of wireless router area coverage (Patten and Ishii, 2007). This physical interaction was comparably ingrained in *Illuminating Clay* (Piper, Ratti and Ishii, 2002) and *Sandscape* (Ishii *et al.*, 2004) workbench architectures which as pictured in Figure 4.4(d) were wirelessly able to measure the volume of 3D models made from clay and sand respectively. and provide feedback. These setups made use either *'high-powered IR'* LED arrays to measure light absorption through sand density or *'range-finder'* laser technology to estimate the 3D input of the workbench which is then directed to computational algorithms. These digital simulation results enable real-time visual projection of information on the physical setup, and this enables users to spatially collaborate and interact with the setup. These have achieved notable results in allowing professional engineers to visualise and iterate on the designs for transport management, slope/drainage landscaping and contour modelling (Ishii, 2006).

Whilst these architectures are able to provide an additional feedback loop to the TUI output and resolve inconsistencies in physical movement, the constructive and electronic complexities of these TUI systems renders them expensive and prohibitive to implement within an educational context. Moreover, the specific technical skills needed for calibration and operation of these TUI systems further hinder the widespread adoption of the TUI architecture outside of dedicated laboratories or commercial installations.

4.1.5 Interactive Surfaces

The popularisation of real-time computer-vision algorithms in TUI frameworks brought about the establishment of TUI interactive surfaces that demanded less costly equipment. This concept was originally pioneered in the *Digital Desk* (Wellner, 1993) architecture, which provided visual feedback to the TUI framework whilst keeping a direct input/output space coincidence. Setups based on this framework made use of top-mounted projectors to display digital content and top-mounted cameras to recognize objects on the horizontal surface as shown in Figure 4.5(a). The notable *Urban Planning Workbench (URP)* shown in Figure 4.5(b), introduced this concept in the architectural design context which allowed architects to experiment with building planning whilst digitally simulating the effects of shadow and the wind (Underkoffler and Ishii, 1999).

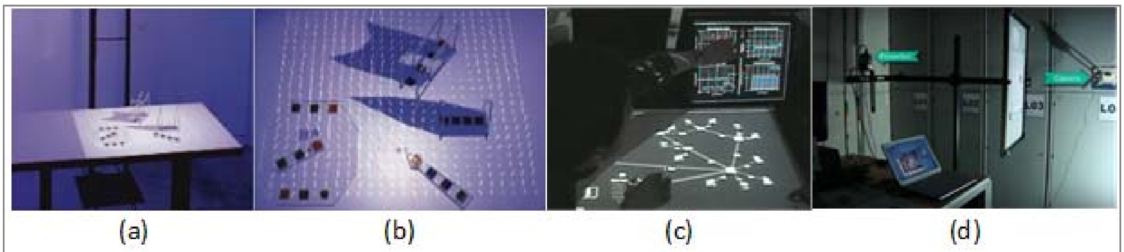


Figure 4.5: Interactive Surface examples:
a) Top-mounted camera and projection setup,
b) Urban Planning Environment (Underkoffler and Ishii, 1999),
c) Vertical / Horizontal Interactive Surfaces (Kobayashi et al., 2006),
d) VeRITable vertical architectural setup (Ricardo A. Corredor, 2008).

Other variant setups, such as *metaDesk* (Ullmer and Ishii, 1997), *Illuminating Light* (Underkoffler and Ishii, 1998), *IP Network Design Workbench* (Kobayashi *et al.*, 2003b), *InterSim* (Arias, Eden and Fischer, 1997), *Build-It* (Rauterberg *et al.*, 1998) and *Disaster Simulation* (Kobayashi *et al.*, 2006) tried to adopt a combination of horizontal and vertical surfaces to manipulate or visualise data as highlighted in Figure 4.5(c). These setups increase their interactive display area as well as include more users on the setup. Regrettably, these mixed architectures confute the intrinsic attributes of TUI systems by severing the physical/digital embodiment of information whilst also invalidate valuable aspects such as perceptual coupling in interaction.

This concept was taken further by *VeRITable* (Ricardo A. Corredor, 2008), shown in Figure 4.5(d), where a vertical TUI architecture was proposed which re-established the input/output coherence. This setup made use of a back-projection screen setup to display digital information and a frontal camera to track fiducial marker symbols. The educational advantage of this system was that it enabled a more effective classroom-based implementation since the TUI setup could be visualised and interacted with by multiple students at the same time. Whilst still encompassing all the attributes of TUI architectures, the vertical concept is heavily restricted from a tangible aspect, since a frontal fiducial marker sticker must be attached to each object for camera recognition (Ricardo A. Corredor, 2008). This, unfortunately, constrains the tangible embodiment and representation of information on familiar everyday objects, thus reducing the effective educational benefits aspired by TUI systems.

4.1.6 Tabletop

The tabletop architectural framework proposed by (Jordà *et al.*, 2007), has garnered substantial interest over the past years due to its potential to adapt to various implementations. These architectures visually track physical objects placed onto a semi-translucent interactive surface which is illuminated by an underneath digital projector. The intrinsic advantage of this setup lies in the fact that the perceptual coupling is achieved by placing both the projector and camera systems underneath the interactive surface, as shown in Figure 4.6, whilst objects are tracked from their optical reflection with the interactive surface. Whilst Dalsgaard and Halskov (2012) have proposed the use of multiple projectors and/or cameras at different angles to avoid surface reflections or enhance capturing capabilities (Klokmose *et al.*, 2014), the advantages brought over by these implementations however, do not justify the increased complexity, and thus the single camera/projector setup proliferated in implementation as shown in Figure 4.6.

The embedding of all the technical components within the tabletop framework, enhances the usability aspect of this architecture, as it enables users to manipulate tangibles freely without surrounding hardware constraints. Furthermore, the tabletop architecture provides also an unrestrictive setup for the employment of commonplace objects as physical manipulatives. This allows the TUI setup to take advantage of the existing skills and familiarity of users with the representative object, thus strengthening the physical/digital representational coupling.

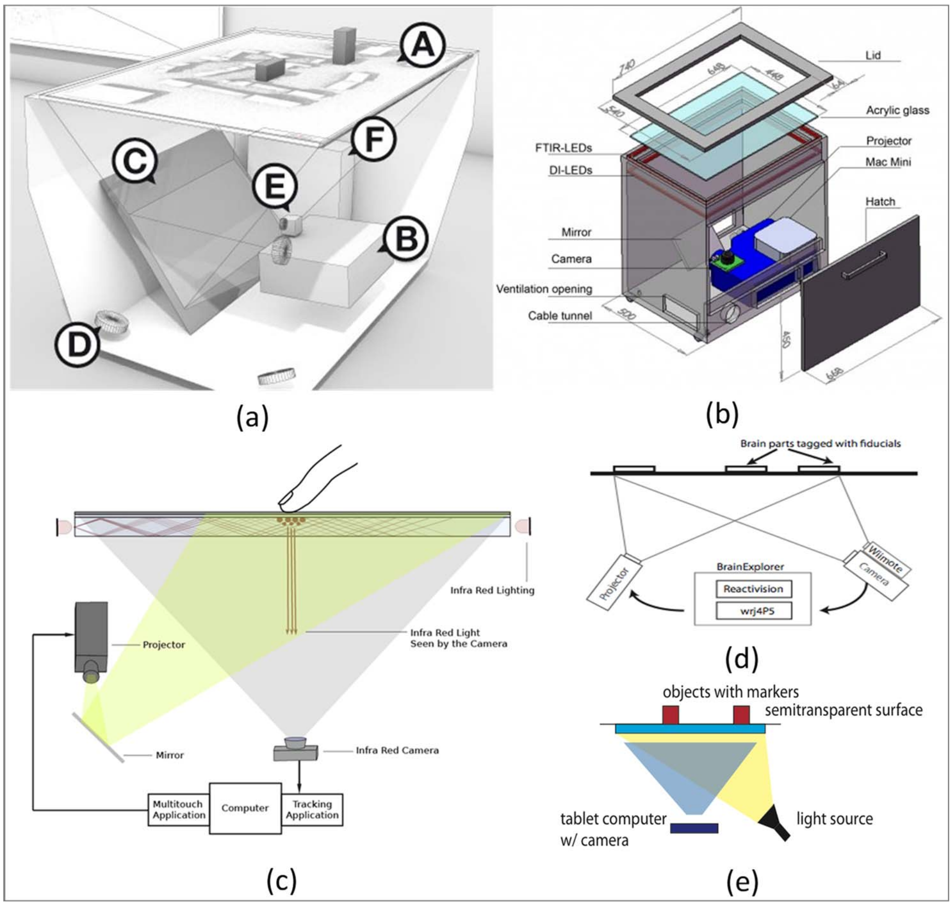


Figure 4.6: Derivations of TUI tabletop architectures:

a) Collaborative Design Platform using IR illumination (Schubert, 2016),

b) Virttable architecture using FTIR-LEDs (Luderschmidt, 2011),

c) Multitouch tabletop architecture using mirrors (Taylor, no date),

d) BrainExplorer architecture using Nintendo WiiTM remote (Schneider et al., 2012),

e) Tablet-based tabletop architecture (Konrad, 2012).

Within educational contexts, tabletop architectures bear an inherent ability to support collaborative experimentation whilst providing a clear understanding of the system functionality via both tangible and digital representations (Maquil and Ras, 2012). Additionally, from a socio-educational perspective, the tabletop approach has also proven as an effective approach to entice students in engaging with each other while at the same time develop their knowledge by collaboratively solving problems (Niu, McCrickard and Nguyen, 2016). Furthermore, the physical movement demanded by interaction with TUI setups invokes utilising a set of spatial skillsets which in turn augment student's thinking and learning capabilities (Rieser, Garing and Young, 1994).

The development of opensource software toolkits to aid in the image processing component of the architecture provided a significant boost towards the popularity of the tabletop architecture, since it minimised the burden on software developers to create TUI systems, and thus focus could be maintained on the design and creation of appropriate GUI/TUI interfaces. Most influential in this respect were the publications of the *ReacTIVision* framework (Bencina and Kaltenbrunner, 2005; Kaltenbrunner and Bencina, 2007b), depicted in Figure 4.7, which provided a symbol based '*fiducial'* marker set which was optimised for tabletop video-camera processing and provided as an API call-back using the TUIO protocol (Kaltenbrunner *et al.*, 2005).

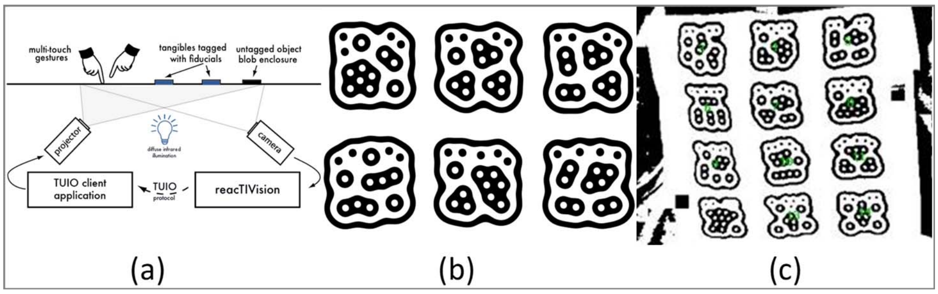


Figure 4.7: Principal elements within the ReacTIVision Framework (Kaltenbrunner and Bencina, 2007b):
a) Architectural tabletop design for toolkit deployment,
b) Fiducial marker set made of unique monochrome patterns providing for optical recognition,
c) Symbol detection and identification of multiple markers through the image processing toolkit.

Whilst the authors in Kaltenbrunner and Bencina (2016) propose a variety of hardware to be adopted for these architectures, as evidenced by architectural representations of Figure 4.6, tabletop systems in literature have been developed using a myriad of different setup configurations (Iacolina, Soro and Scateni, 2011). Whilst this flexibility enabled the faster and popular deployment of tabletop TUI architectures, the ad hoc design and development of this TUI architecture thus far lacks formalisation on effective design considerations (Sheridan *et al.*, 2009). This is particularly eminent in the educational domain, whereby literature has evaluated numerous TUI system deployments with various hardware configurations and seldom accounted for bias in results due to the different technological implementations. Moreover, to the non-technical educator, the bewilderment of options often results in increased difficulties and confusion in designing a suitable tabletop setup.

Whilst current research has focused on contextualization of TUI systems for adoption across the spectrum of educational institutions, the considerations needed for adequate TUI architectures in campus and college environments has been largely overseen, thus suppressing the effectiveness and further proliferation of TUI systems in education.

4.2 Proposed TUI architecture

In light of the limitations outlined in TUI architectural literature and the lack of formalised design for a successful TUI deployment in education, this dissertation section outlines various design considerations for a smart TUI tabletop implementation. The research contribution of this dissertation chapter considers the specific requirements imparted on a TUI system when used within a higher educational context and proposes innovate solutions to formalise an effective design and implementation of such a novel technology domain.

4.2.1 Requirements Elicitation

The deployment of a TUI system within an HEI environment instils requirements which are peculiar to the context of teaching and learning. From a system specifications perspective, the maximisation of the interactive tabletop surface area is a critical provision for the development of complex algorithmic representations (Grote *et al.*, 2015). This would also allow the utilization of several tangible objects concurrently, hence allowing the deployment of convoluted TUI interactions.

From an accessibility perspective, the TUI design needs to allow multiple users to interact with the surface simultaneously. This prerequisite affords the system to exploit an experimental and collaborative learning pedagogy whilst allowing the TUI system to be used by small cohorts of students together within seminar/laboratory sessions. Intrinsically, this requirement implies that the system needs to maximize the perimeter of usage for students, whilst also cater for students with different physical accessibility needs.

Within a HEI context, the design of a useable and convenient TUI system also needs to allow the system to be easily transferable between different laboratories and lecture halls. Thus, from portability perspective, the system necessitates a lightweight construction that can be easily transported within different buildings and compactable enough to fit inside conventional elevators.

Moreover, this also implies that the system needs to be comfortably and quickly assembled/dismantled with no technical calibration procedures needed prior to usage.

Lastly, from an educational perspective, the TUI technology needs to ensure that students are able to focus on the conceptual subject being thought rather than the usability aspects of the system. This entails the need to simplify the interaction styles employed during operation whilst embedding assistive cues to aid with the teaching and learning of the specific HEI concepts.

4.2.2 Physical Design Considerations

The aforementioned requirements imparted a number of form-factor constraints on the system's physical design. Based on the architectural literature investigated and the educational affordances of different TUI setups, a tabletop architectural model was selected as most suitable for HEI integration. This was planned for native compatibility with the *ReacTIVision* computer-vision framework and adopted the *MCRpd* (Ishii, 2008a) conceptual model approach as outlined in the designed framework in Figure 4.8.

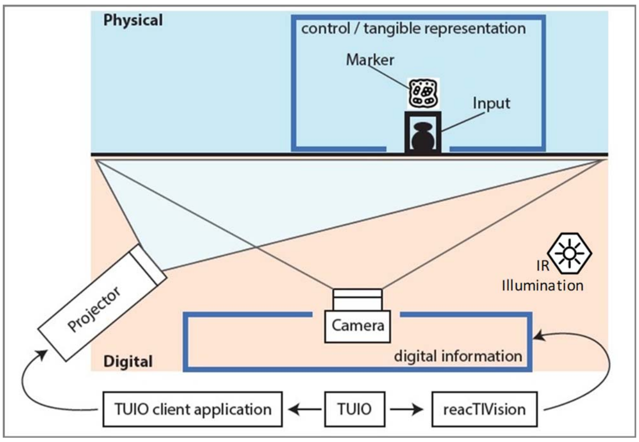


Figure 4.8: Tabletop tangible interaction architectural model adapted for TUI in HEI

A fixed structure design was deemed necessary as to abide by the requirement to provide an easy to assemble and setup tabletop which does not require the need of technical expertise to calibrate the various active components. Abiding with the architectural design guidelines by (Neufert, 2002), comfortable reach and usability were ascertained by limiting the overall height for standing users to comfortable interact with a tabletop design to a maximum of 90cm as illustrated in Figure 4.9. This height was also identified in order to allow a group of students to gather around the TUI system and ensure that they can all easily visualise the entire tabletop area. From an education aspect, the design consideration would thus be able to allow all encircling students, even ones not directly using the TUI system, to observe the information being projected as well as all the TUI component's being used. This would intrinsically aid the delivery of the chosen subject as well as heighten the engagement of the entire student cohort.

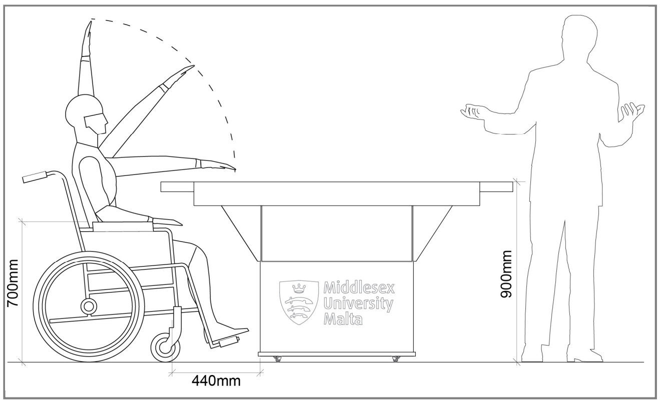


Figure 4.9: TUI form-factor in consideration of accessibility and usability constraints

Whilst adhering to the accessibility constraints, the form-factor of the proposed TUI system needed to maximize the interactive surface area dimensions which impacts critically the scope and usability of the smart technology. To address this requirement, a 4:3 aspect ratio was selected for the interactive surface design as intrinsically this would yield a larger workable area for TUI system whilst still retaining comfortable usability for single or multiple users. Based on the current projectors available commercially and their throw-ratio capabilities, a tabletop prototype was constructed from cardboard material, as pictured in Figure 4.10. This allowed the ability to measure the maximum interactive capacity obtainable as well as refine various design considerations.

Figure 4.10: Cardboard prototype for design and measurement

This agile approach to design provided invaluable benefits towards the development of this dedicated architecture. Making use of a subset of six higher-education students who were asked to interact with various sections of the interface during alpha-stage evaluation, enabled the identification of several strengths and weaknesses in the design. During this exercise, wheelchair dimensions were also taken into consideration to assess the accessibility from physically disabled users when encircling and interacting with sections of the interactive surface. This allowed for addressing these considerations in an iterative manner which, through the prototyping capabilities of cardboard, enabled for the immediate improvement of design epochs and eventually aided the accurate dimensional measurement of each physical component. This agile development methodology led to the design architecture in Figure 4.11 and the generation of shop drawings attached in Appendix A.

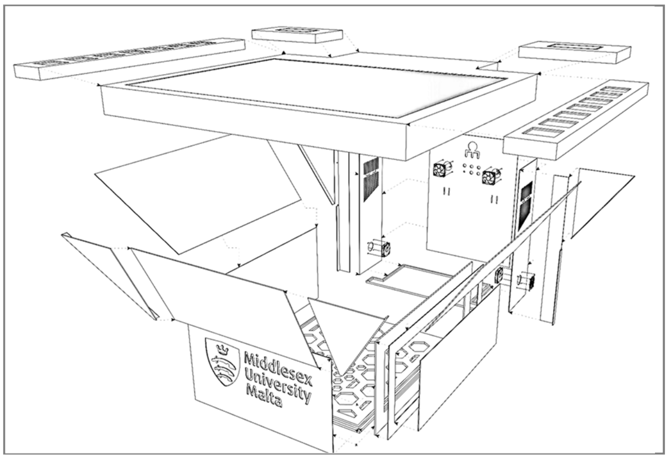


Figure 4.11: Assembly design of the Component-based TUI architecture

The portability constraint was abided by in the proposed design by undertaking numerous considerations in both material selection and construction. Aluminium laminated composite was chosen as the ideal material to build the main structure of the table. This material posits several advantages over traditional wood including; smooth finish, overall strength, absence of splintering, and less environment-dependent alterations or expansions which could lead to misalignment of the table components from the interactive surface. Furthermore, owing to the inherent rigidity of this material, 3mm thick sheets provided enough structural strength, whilst significantly curtailing the overall weight of the TUI system. To further contribute to the lightweight construction of the system, Polyvinyl chloride (PVC) boards where installed at the base of the table, which as seen in Figure 4.11, was perforated in a honey-comb structure to curb weight whilst aiding air-flow for cooling of active components inside.

From a construction perspective, the portability constraint necessitated various transportation and storage considerations. To minimize the storage footprint of the TUI system whilst also ensuring that the physical architecture can pass through standard door and elevator openings without the need for complete dismantling and reassembly, a foldable panel-design was proposed as shown in Figure 4.12.

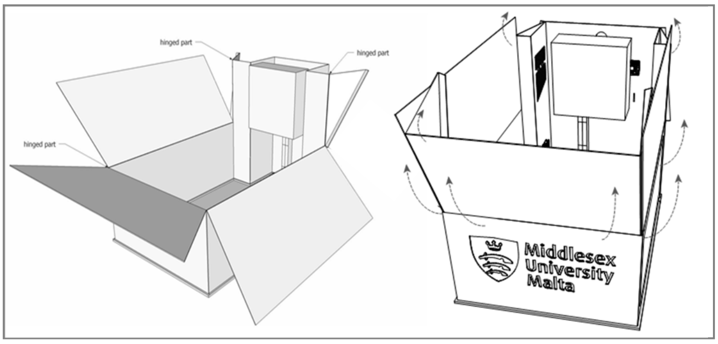


Figure 4.12: TUI form-factor in consideration of portability constraints

These panels were held in their different pre-set positions using neodymium magnets, hence rendering the proposed system easily compacted/unfolded. To mitigate the burden of technical calibration needed to align the camera setup and digital projection to the interactive surface, all active components are permanently affixed to the honeycomb base, thus retaining accurate positioning during transportation and reassembly of panels.

Transportation of the designed TUI system throughout the campus lecture halls and through elevators was rendered possible using castor wheels and the appropriately designed hinged side panels as illustrated in Figure 4.12. To aid in the storage, maintenance and transportation necessities of the TUI architecture, the setup was designed to be easily dismantled into 3 functionally-distinct separate sections as shown in Figure 4.13.

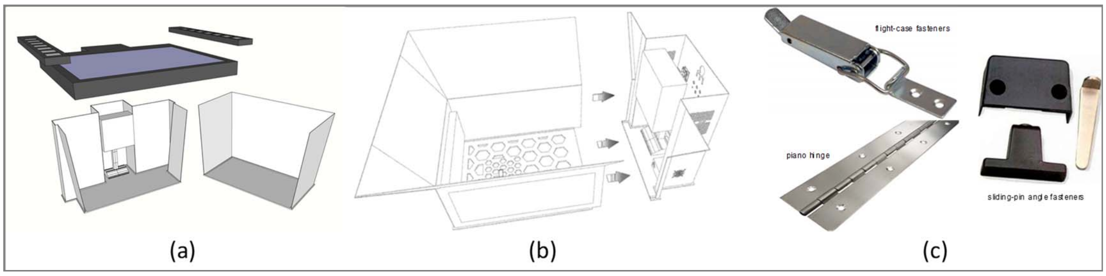


Figure 4.13: Form-factor disassembly:

a) individual separate sections

b) base-section coupling

c) attachment options for ease-of-installation design

To curb assembly and maintenance time needed whilst adhering to the ease-of-install design criterion, a variety of appropriately selected attachment options were implemented. *'Flight-case fasteners'* were used to interlock the base-section coupling designed in Figure 4.13(b). The foldable design in Figure 4.12 was achieved using *'piano hinge'* along the panel seams, which whilst allowing the uniform folding of panels to locked positions, further acts as a tight fit along the seam. The complete assembly/disassembly of component panels in Figure 4.11 from each other for *'flat-package'* transportation was designed for tool-free implementation using *'sliding pin angle fasters'* shown in Figure 4.13(c). This enabled a solid interlocking mechanism which can be assembled by a sole user, does not require any technical/mechanical skills and allows the complete assembly from *'flat-pack'* in a contextually feasible timeframe of 10 minutes.

The top-section of the designed TUI architecture harboured the tabletop's interactive surface together with additional smart-peripheral attachments as shown in Figure 4.14(a). A 3mm semi-transparent acrylic pane was used for the interactive tabletop covering a surface area of 1.3m^2 (1.3m x1.0m). This design decision took into consideration the ideal density and surface thickness for TUI operation. The material opaqueness and thickness needed to allow the projected image to be visualised from underneath illumination, diffuse the projected light *'hot-spots'* whilst at the same time curtailing on thickness to avoid light refraction artefacts. Moreover, the material density required a degree of translucency to provide clear capture of fiducials on the surface from an underneath camera.

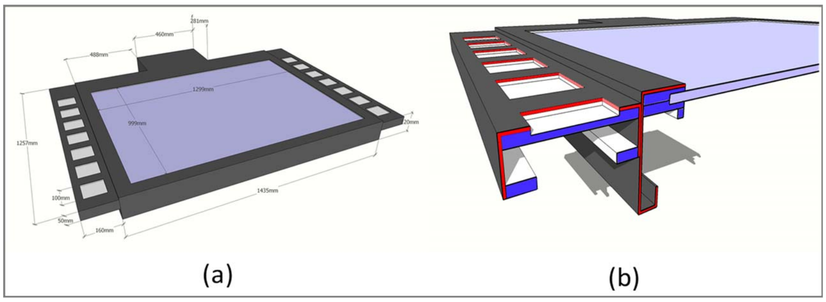


Figure 4.14: Top-section physical design:

a) tabletop interactive surface with peripheral attachments

b) structural design for interactive and construction rigidity.

From a construction perspective, this sectional component needed also to provide structural rigidity to the assembled system. The TUI structural design demanded the consideration of adult HEI students leaning weight on the assembly, and thus a solid frame made from aluminium laminated composite was designed for structural rigidity as shown in Figure 4.14(b). This material was further used to create the side and folding panels of the table construction and its lightweight property enabled the overall system to curtail significantly on its overall weight. As shown in Figure 4.15, the base component was cut-out in a honeycomb pattern so as to retain structural strength whilst at the same time curtailing on weight and facilitating air flow by accessing cool air from beneath the table. The central area was further added with smaller honeycomb structures, which enabled the provision of a flexible attachment area for camera positioning underneath the interactive surface. Setup and maintenance accessibility was also designed by means to an access panel on the left-hand side which was snapped in place using six powerful neodymium magnets.

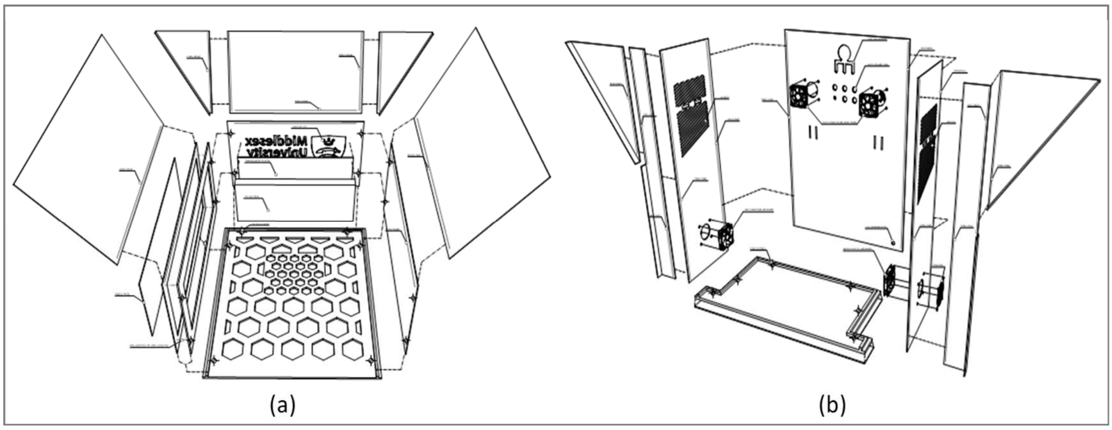


Figure 4.15: Assembly design of the architectural front and back-sections

The rear-section of the table was mainly designed to harbour the technical components of the TUI system including projector and lighting elements. To this end, a number of perforations were appropriately undertaken to bolt the projector's base to the table as well as to allow for power/data cable management for the TUI system. Furthermore, a series of air ventilation perforations were designed on the aluminium side panels, as shown in Figure 4.15, which provided passive air-cooling functionality to the active components.

4.2.3 Technical Design Considerations

The designed tabletop architectural model, depicted in the Figure 4.8 framework, illuminates the interactive surface using underneath projection. This option was selected to eliminate the projection shadows which adult-sized users would experience whilst interacting with tangible objects. These requirements led to the selection of a short-throw projector to be installed in the system which was able to illuminate the 1.3m^2 area within a projection distance of 0.9m as shown in Figure 4.16(b).

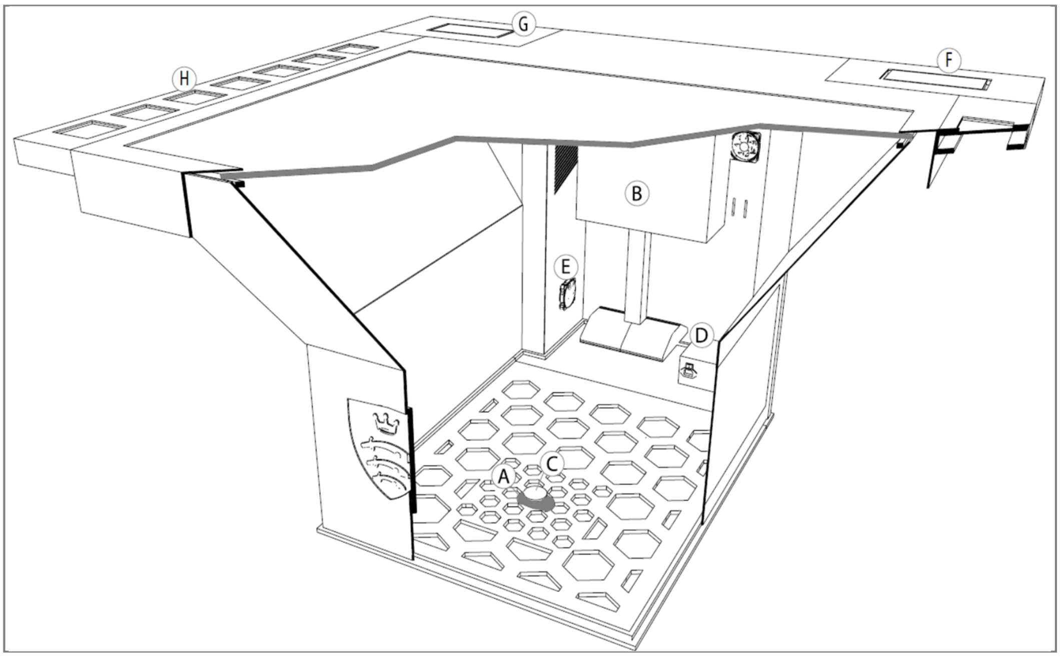


Figure 4.16: Construction cross-section of the proposed smart TUI system design:

a) Wide-angle CCD camera with IR band-filter,

b) Short-throw projector,

c) Honeycomb PVC floor structure,

d) Processing computer,

e) Active cooling system,

f/g) Raising & Revolving TUI platforms,

h) Side trays with illuminated TUI placeholders

The TUI framework provides feedback to the system from the recognition and identification of objects manipulated by the user using optical sensing. To avoid capturing occlusions from interacting users, a wide-angle CCD-sensor camera was installed underneath the surface as illustrated in Figure 4.16(a). To further aid the imaging quality rendered by the camera, an infrared (IR) light 830nm band-filter was attached to the camera and an array of IR LEDs installed inside the table. Apart from flooding uniformly the captured area, this design approach aids in mitigating the light intensity variation arising from the projected images with different colour brightness and consequently aids in removing imaging constraints for TUI software development.

The electronic components were centrally wired and controlled through a switch console designed on the back section. The wiring diagram in Figure 4.17 outlines the power cabling design of the switch console together with the 3D printed switch labelling. This design schema was developed to further facilitate the TUI setup and operation in line with the portability requirement.

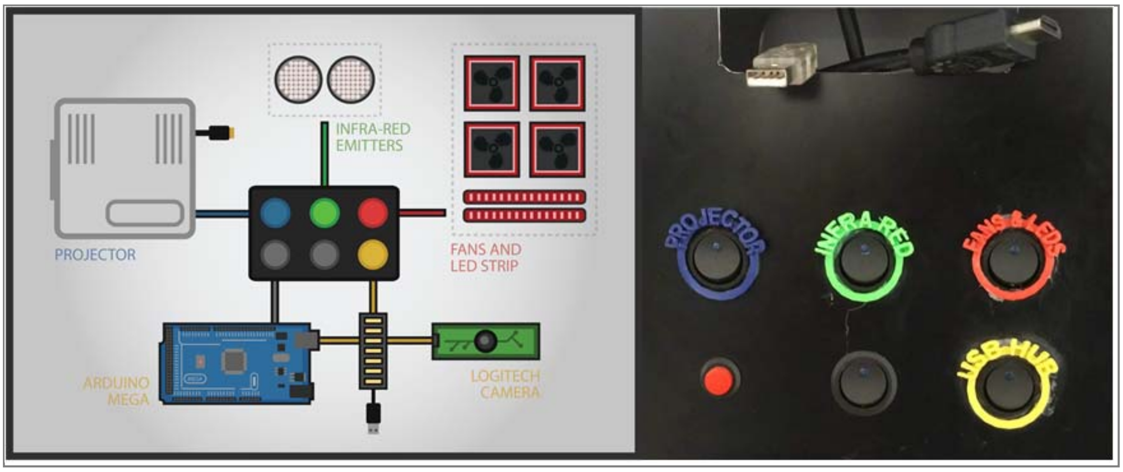
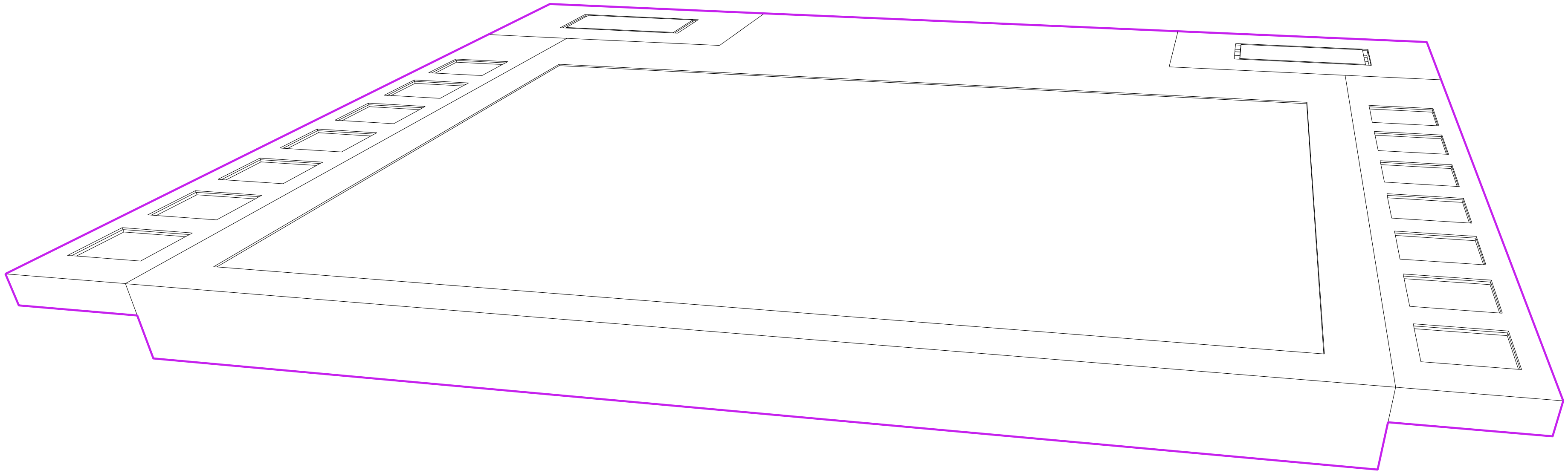


Figure 4.17: Back panel electronic power switch console

Air circulation and cooling was also considered for the architectural design, since the enclosed tabletop configuration contained all the active components in a confined space. To this end, an active cooling approach was designed which as shown in Figure 3.18, generates a cooling airflow amongst the camera and lighting components. The net cost of procuring and building the proposed architectural components is tabulated within Table 4.1 with further details of the technical specifications of the sourced components.

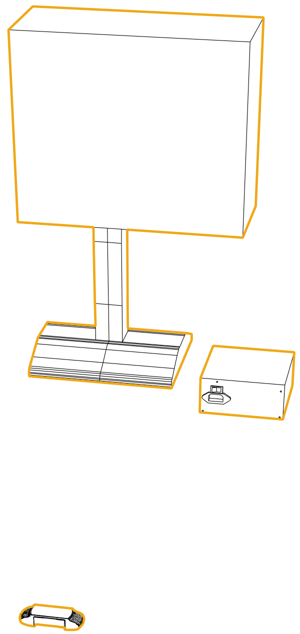
Table 4.1: Bill of materials and procurement costs of the proposed TUI architecture

Determinant	Cost	Source
Sony VPL-SW536 Short Throw Projector • **Throw Ratio:** 0.27-0.29 • **Technology:** LCD • **Lumens:** 3000 **Resolution (Native):** 1280 X 800	£874.08	www.amazon.co.uk
Laser Cut Tangible User Interface Table • **Body:** 3mm aluminium – matt black/white • **Surface:** 10mm clear acrylic (1420 x 1560mm) • **Base:** 20mm routed plastic • **Design:** As per provided 3D diagrams **Mounting:** Panels supplied loose	£1793.61	Creative Works Ltd, Malta.
Wide Angle Camera • **Lens:** 120° ultra-wide-angle lens • **Frame Rate:** 30fps at Full HD • **Zoom:** 4x digital zoom in Full HD **Resolution (Native):** 1920 X 1080 Full HD	£56.76	www.amazon.co.uk
Additional Components • **Peripherals:** Switches / Fans / LEDs • **Construction** Material: Rivets / Hinges / **Assembly :** Hand tools procured separately	£350	www.ebay.co.uk Local Ironmongeries
Total Procurement Cost	**£3075**	



Legend:

Table-top



Peripherals | Projector, camera, power supply etc.

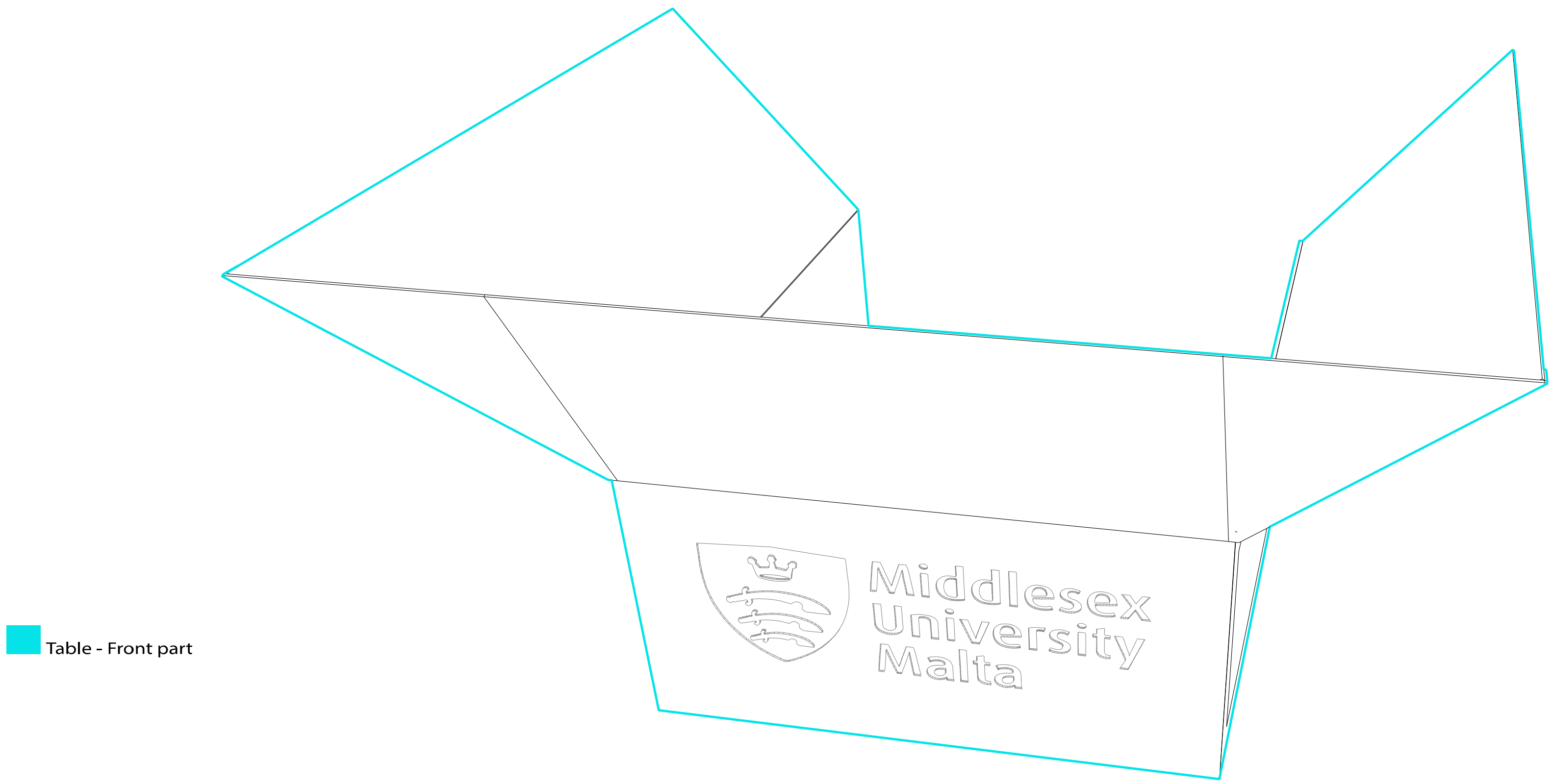


Table - Front part
Middlesex
University
Malta

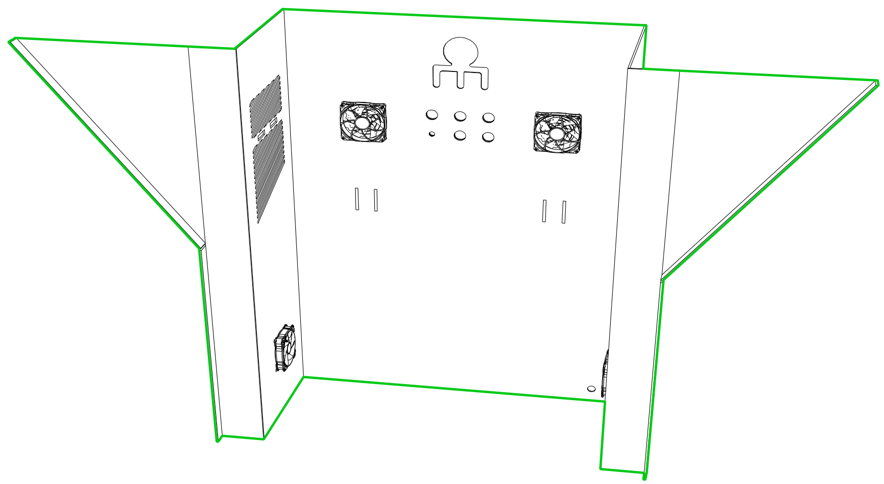
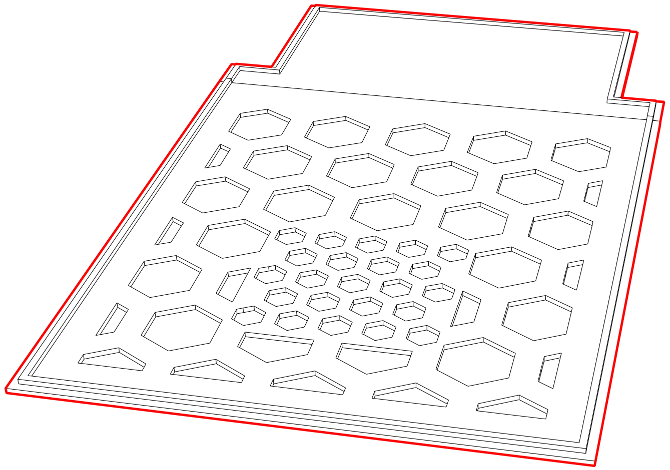


Table - Back part



Base - Front and back part

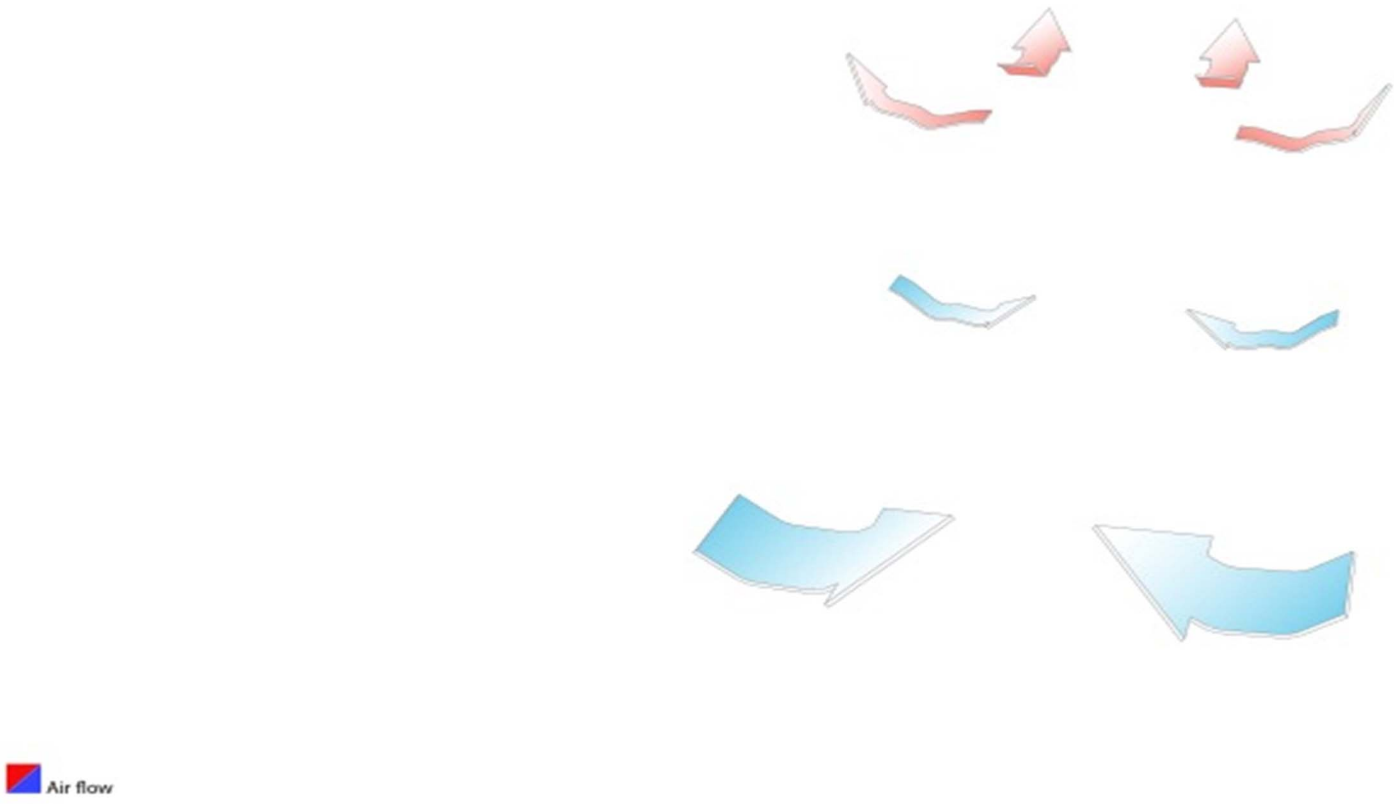

Air flow

Figure 4.18: TUI architecture assembly design using layered component sections

4.2.4 TUI Peripherals

In contrast to conventional TUI tabletop setups proposed in literature; (Sheridan *et al.*, 2009; Iacolina, Soro and Scateni, 2011; Luderschmidt, 2011; Schneider *et al.*, 2012; Schubert, 2016) the proposed TUI architecture embodies a number of innovative peripheral tangible technologies to enhance the effectiveness of teaching and learning in higher education. Designed in a modular approach to facilitate transportation and storage, the proposed system makes use of the TUI-enhancing technologies, illustrated in Figure 4.19 and Figure 4.20, to help engaging students whilst enhancing the usability aspects of TUI systems. These smart modules, which are attached to the sides of the tabletop interactive surface are controlled through an Arduino Mega*TM* microprocessor and directed via serial communication from the TUI software executed through the computer.

From an educational perspective, these peripheral TUI components were designed to heighten the sense of engagement by adult-users whilst still providing persuasive interaction for usability direction and intrigue. Making use of appropriate timed behavioural-change triggers as modelled in (Fogg, 2009), the interactive peripherals provide cues for users to select, utilise or place back a tangible object. In line with the EAST behavioural-insights framework (Service *et al.*, 2014), these tangible interfaces provide lighting and movement interaction that encourage, support and enable students whilst interacting with the TUI architecture. This functionality, aligns with Krug's (2006) usability theory in maintaining the user's concentration on the TUI application without distracting focus for manipulating controls.

The placeholding trays, shown in Figure 4.19, were designed as attachments on either side of the system's tabletop which serve to hold tangible objects that would not be currently in use. Apart from reducing object clutter on the interactive surface, the placeholders were embedded with individually-controlled RGB LEDs. This functionality was designed to provide interactive feedback to the user whilst using the TUI system using a combination of flashing and/or colour-coded lighting. These algorithmically controlled cues were in fact able to direct student’s activities by either prompting the selection/removal of a particular object or even evidencing the options of object choice for the student as a result of a previously performed action on the interactive TUI surface.

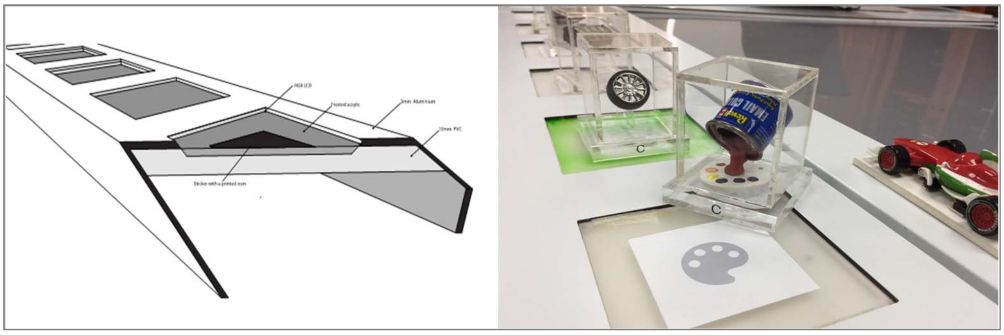


Figure 4.19: Side trays peripheral section with illuminated TUI placeholders

The interactive TUI revolving and raising modular platforms, illustrated respectively in Figure 4.20(a) and Figure 4.20(b), are contrastingly used to provide students with a different interactive experience. Marking use of individually-controlled servo motors and integrated RGB LEDs, these modular devices are able to reveal a magnetized tangible object that would not have been available beforehand. By capitalizing on the curiosity aspect of an appearing tangible object throughout the execution, the proposed TUI architecture is able to positively condition the student’s interaction to investigate the effect of the appearing object. Furthermore, the revealing effect of these technologies intrinsically heightens interest within students and thus serves to enhance their engagement with the TUI system.

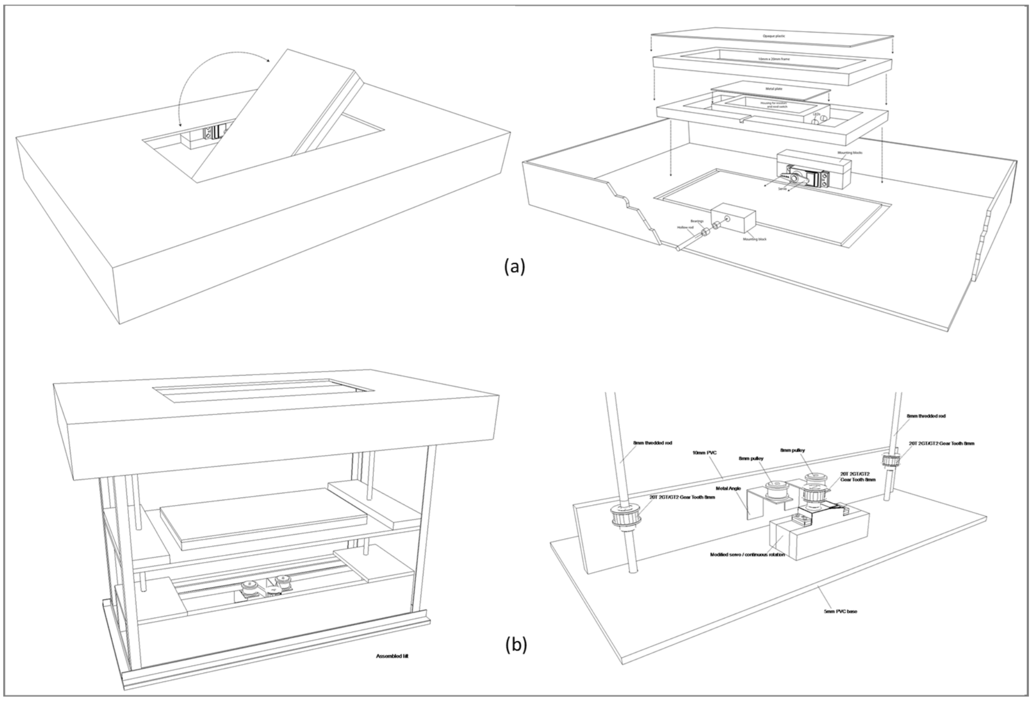


Figure 4.20: Innovative TUI smart technologies embedded in proposed system:

a) Revolving TUI platform

b) Raising TUI platform

4.3 Evaluation of Tabletop Architecture and Discussion

To evaluate the applicability and effectiveness of the designed physical TUI architecture shown in Figure 4.21(a) for HEI utilisation, a TUI case-scenario as elaborated in section 5.7 was implemented. A deployment context was provided for undergraduate computer science students reading a first-year module on *'Introduction to Java programming'*, which as pictured in Figure 4.21(b) enabled the utilisation of the proposed tabletop architecture. To obtain independent observation and feedback on the physical TUI architecture design and the efficacy of the designed interaction modules whilst reducing influence of the GUI application, a tailored selection of feedback questions from the TAM4Edu model, described in chapter 6, were adopted. The latter provided a quantifiable insight on the usability and acceptance of the designed tabletop TUI architecture.

4.3.1 Evaluation Methodology

Student selection was based on a purposive sampling approach, which provided the opportunity for the entire cohort undertaking a particularly relevant module to participate within the study. The selected class was composed of 41 students ranging between the ages of 17 to 39. The students were not forewarned about the upcoming research study and following their normal attendance to class, a split was undertaken to divide the class in two groups. Twenty (20) students were randomly chosen for inclusion within the experimental group, whilst the remaining 21 students were grouped to form part of the control group.

Subsequent to the split, each group underwent a lecturing delivery of the same topic in a different room. The control group were introduced to the concept of object-oriented programming via a traditional lecture. This session made use of conventional educational technologies such as an overhead data-projector, smartboard and a PC laboratory. Conversely, the experimental group were subjected to a lecture of the same technical object-oriented concepts using the proposed TUI architecture deployment integrated with an appropriately designed software as illustrated in Figure 4.21(c). Whilst evaluation of the knowledge gain and the TUI software application where not sought after within this methodology, a number of considerations where nonetheless taken to curtail the potential of lecturer bias between tuition sessions which could have affected student perceptions. To this end, both evaluations were conducted for a fixed-time period by the same designated lecturer responsible for introducing programming, and an identical car-based analogy was used to explain object-oriented concepts. Students and lecturers interacted naturally with respective available technologies during the evaluation sessions, and the experimental conditions outlined were monitored by an external academic throughout the experiments so as to ensure a minimization of bias between the control and experimental groups.

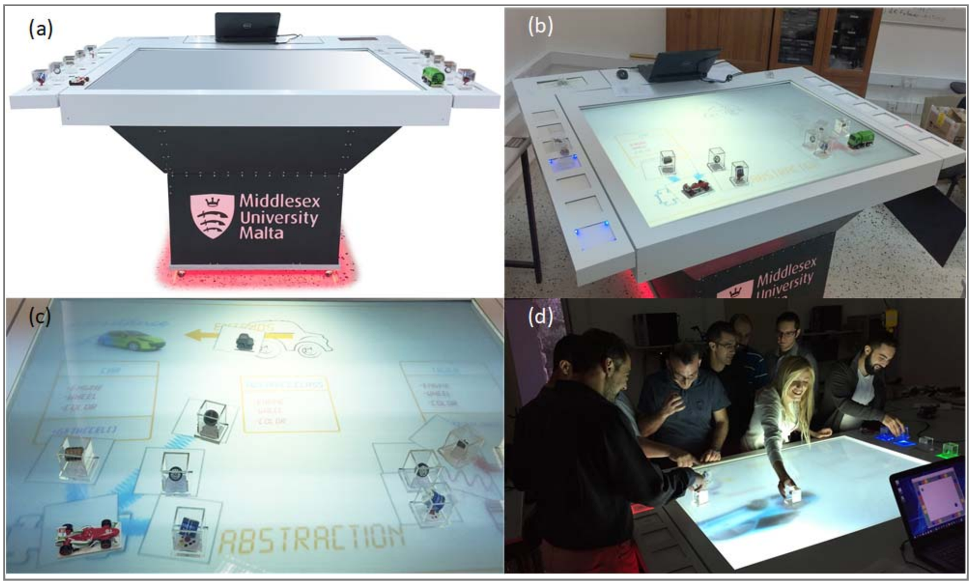


Figure 4.21: Evaluation of designed TUI architecture for HEI:

a) Assembled TUI architecture,

b) TUI architecture setup for evaluation,

c) Object-Oriented Programming Concepts using TUI architecture,

d) Evaluation session undertaken with HEI students.

Upon completion of each respective session, students were provided with a short survey to quantify their experience using either technology. Five (5) statements, adapted from the TAM4Edu framework described in chapter 6, were posed to each student, for which a seven-point Likert scale was adopted to rank preference, ranging from strongly disagree (score: 1) to strongly agree (score: 7). The questions were structured to assess different aspects of the student's teaching and learning experience as follows:

- Perceived Usefulness (PU):
  Through the technology I have learnt the subject effectively.
- Perceived Ease of Use (PEU):
  The used technology was rather difficult to operate.
- Perceived Enjoyment (PENJ):
  I had fun using the educational technology.
- Usability (USE):
  The feedback was intuitive.
- Perceived Lecture Attention (PLA):
  I felt very attentive during this lecture.

4.3.2 Results and Discussion

The survey technique was designed to provide a quantitative evaluation of the student's perception on the use of the proposed smart TUI design within the context of HEI lecture delivery. The obtained results from participants were tabulated in Figure 4.22 whereby the responses for each question by the different student groups are averaged.

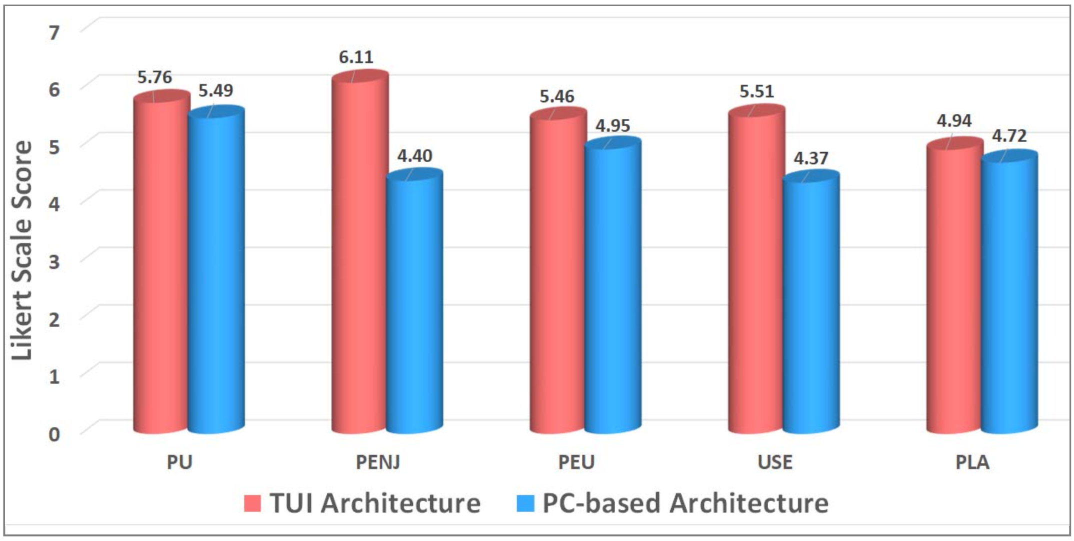


Figure 4.22: Student evaluation of proposed TUI system with respect to traditional educational technologies using a Likert-scale score ranging from strongly disagree (score: 1) to strongly agree (score: 7).

The comparative results in Figure 4.22 clearly highlight that the overall experience of HEI students using the proposed smart TUI system was enhanced during their educational session. Major improvements were in fact measured, at a statistical significance of ($\rho < 0.05$), on the attributes of usability and perceived sense of enjoyment, whereby students who engaged with the TUI architecture registered considerably increased scores with respect to the traditional lecture control group.

A qualitative interview with the lecturer following both sessions also corroborated the observation that student engagement was significantly higher during the TUI session with respect to that exhibited by the control group. The intuitive cues embedded in the architecture intrinsically prompted students making use of the TUI system to discuss and collaborate during the lecturing session. These observations were substantiated by data gathered from all participants within the survey which outlined that the TUI setup provided a more immersive experience. Furthermore, objective time measurements recorded by the external moderator on both sessions, experimentally outlined that TUI group required 19% less time to grasp the concept successfully with respect to the control group which utilized the entire session duration to understand the conveyed concept. Whilst these results could have been biased by the application software developed within the experimental TUI framework, the analysis of TUI frameworks against GUI counterparts for academic effectiveness was beyond the scope of this evaluation experiment (undertaken in subsequent evaluations within chapter 5), and thus students where solely questioned on their engagement perception.

On the other hand, it was noted that handling large groups becomes increasingly challenging with the TUI system, and whilst students interacting with the interface sustained consistent interest, those farther away from the perimeter tended to be less involved with the TUI explanation. Thus, it was noted that the proposed architecture would be optimally suited to handle up to eight (8) individuals at one time, whereby each student would physically be able to interact appropriately with the tabletop design. This threshold is substantiated also from an educational perspective, where it was noted that; larger student groups resulted in a deterioration of personal engagement with the system and thus an eventual reduction on the potential teaching and learning experience that can be obtained from the designed TUI tabletop architecture.

Chapter 5
Deployment of TUI Frameworks in HEI

Based on the proposed tabletop architecture in chapter 4, this chapter will describe the adoption of TUI frameworks for teaching and learning abstract computational science and technology-based concepts in higher education. The design, development and deployment of eight distinctive educational TUI frameworks; inclusive of considerations on hardware elements, software applications, tangible manipulatives and interaction designs will be structured sequentially within separate sections.

For each distinct HEI threshold concept, the respective section critically outlines a literature review on the educational technologies currently adopted within the field of tangible technology as well as alternative computer-based approaches. Built of these reviews, each section details the design of a TUI framework to educate on the conceptually abstract or complex topics identified. A comprehensive description is provided on the tangible design considerations undertaken within each TUI framework together with the interaction developments proposed. Through their respective sections, the TUI frameworks proposed in this research are explained according to their varied design elements. Thus, the contributions undertaken by this research in TUI education for HEI contexts are elaborated in accordance to the various design methodologies adopted for appropriate tangible objects, graphical software architectures as well as suitable interaction paradigms. The effectiveness of each TUI framework is subsequently evaluated within each respective section whereby an experimental methodology is undertaken in real-life deployment of the developed systems within undergraduate programmes at HEI institutions. Evaluation results are statistically analysed to assess the effectiveness of the proposed TUI framework to aid teaching and learning with respect to educational technologies conventionally adapted in each educational context.

5.1 Evaluation Methodology Design

The evaluation practice to effectively measure the value imparted by the proposed TUI frameworks was undertaken by amalgamating numerous aspects from evaluation methodologies used to concretize the understanding of abstract and complex concepts. The understanding of meaningful learning imparted by the proposed educational pedagogies was undertaken in line with the learning models proposed by Jarvis (1992, 2014) and Novak (1998, 2010) which measured learning as the integration obtained from the newly acquired knowledge in relation to prior knowledge (Hay, 2007). Thus the a priori knowledge of students is initially measured to develop an individualistic baseline from which learning and knowledge gain can be calculated and assessed (Hay, Kinchin and Lygo-Baker, 2008).

In TUI evaluation within education, the authors in Catala *et al* (2011) and Skulmowski *et al.* (2016) introduce the use of written or verbal tests to assess the level of understanding of individuals prior to learning and follow the tuition session with a secondary assessment to evaluate the effects of the tangible interface on knowledge gain. Moreover, by integrating multiple-choice questionnaires (MCQ), this differential assessment methodology was adopted for more variate education technologies within HEIs (Lan, 2007).

The discrimination and respective importance of assessing TUI architectures for both ‘tell-and-practice’ and ‘inventive’ aspects were further outlined by Schneider and Blikstein (2016). These two educational pedagogies provide avenues for acquiring different knowledge experiences, whereby the former promotes students to constructively practice their understanding in succession to lecturing instruction whilst the ‘inventive’ approach allows students to experimentally learn by adapting knowledge to problem-solving scenarios (Ertl, 2010; Azizinezhad and Hashemi, 2011; Schneider and Blikstein, 2016). When undertaken in conjunction with traditional lecturing educational technologies, the order of the evaluation sequence when sequentially subjecting students to both a TUI architecture session and a traditional lecturing in an inverse order has yielded significant differences (Hansen and Halskov, 2014). Whilst these results demonstrated significant benefits for adopting and experimenting with TUI frameworks prior to undertaking conventional learning approaches, the introduced bias by sequential exposure renders the evaluation methodology unable to comparative evaluate the effectiveness of both educational technologies.

To this end, each section within this chapter describes respectively the different evaluation methodology designs undertaken within each experimental context. This is followed by a statistical analysis on the obtained results from each evaluation with a critical discussion on the concluding inferences towards answering the research question investigated in this study.

5.2 Computer Network Protocols

The teaching and learning of computer network principles at undergraduate levels are commonly regarded as a challenging domain (Linge and Parsons, 2006; Sarkar and Petrova, 2011). Attributing to the perception of this difficulty is the inherently abstract nature of the subject's fundamentals, as well as the inability to visualise the networking principals, protocols and algorithms used in communicating data between inter-connected devices (Hnatyshin and Lobo, 2008; Shanmugam *et al.*, 2011). Furthermore, the dedicated and expensive laboratory equipment used when exposing the students to computer network devices, most often stifles the university students with inflexible on-campus lecturing timings (Gasparinatou and Grigoriadou, 2011). Moreover, the limited hardware equipment available within laboratories for students further restricts the opportunities for attending students to actively engage with the taught conceptual processes (Shanmugam *et al.*, 2011).

5.2.1 Educational Technology for Computer Networks

Intending to address these frequently faced predicaments, a variety of computer-based network simulators have been developed, ranging in nature from commercial to research-oriented (Goldstein *et al.*, 2005). The open-source *JASPER* package (Turner and Robin, 2001), is a Java-based education and research simulator aimed at explaining the sequential nature of protocol communications using timing diagrams. As a more advanced educational software, *iNetwork* (Sandrasegaran and Trieu, 2006), aims to provide students with the ability to configure basic networking components at parameter level, thus gaining insights in common protocols such as domain name server (DNS) and dynamic host configuration protocol (DHCP). *DlpSim* (King, 2011), a similar software package targets the simulation sequence of data-link layer protocols for classroom use. A more comprehensive software aimed at student experimentation is *cnet* (McDonald, 2015), which simulates various data-link, routing and transport layer protocols on Local Area Networks (LAN)s and wireless links. Whilst the software is freely distributed, the setting up the network topology can prove a challenging task to novice students. Conversely, *WLAN-Designer* (Li, Yong and Wu, 2009) is a simplified, easy-to-use, web-based implementation for classroom teaching and learning which however only provides access to wireless LAN modelling.

Commercially, a number of alternative computer-based simulating software is available for explaining computer network principles. *OPNET* (SteelHead, 2017) is a highly popular software adopted by researchers and practitioners alike for the complete simulation and modelling of computer networks. Whilst adopting straightforward graphical user interfaces, its widespread functionality and customization necessitate a good network understanding, thus making it only suitable mainly for advanced networking classes (Lacage and Henderson, 2006; Sarkar, 2008). A similarly powerful text-based simulator is *NS-3* (NS-3 Consortium, 2011), which further provides comprehensive performance analysis and modelling of computer and communications networks. Finally, the most prevalent commercial educational computer networks simulator is the Cisco network academy^{TM} *Packet Tracer* package (Systems Cisco, 2010; Jesin, 2014). The latter has long been the focus of pedagogical studies and is chiefly renowned for its ease-of-use and visualisation features (Janitor, Jakab and Kniewald, 2010; Smith, 2011; Petcu *et al.*, 2013; Noor, Yayao and Sulaiman Sumzaly, 2018).

Whilst several computational network simulators have been developed to aid in the teaching and learning of computer network principles, these have all been based on traditional PC technology (Kobayashi *et al.*, 2003a). Thus, whilst graphical user interfaces (GUI)s varied amongst these implementations, the users' interactions were conventionally constrained to mice and keyboards for input and digital monitors for output on every system (Ishii, 2008b). This computing setup, albeit largely available, provides inherent limitations for the undertaking of collaborative network design and study by students (Kobayashi *et al.*, 2003a). Furthermore, since visualisations are limited to two-dimensional (2D) representations of the network devices this imparts a further additional layer of abstraction from actual hardware (Ullmer, Ishii and Jacob, 2005).

5.2.2 Computer Networks TUI Framework

In light of the above constraints, this section proposes the adoption of an interactive TUI framework for comprehending the abstracted aspects of computer network protocols within Higher Educational Institutes (HEI)s. Specifically, the research will analyse the effectiveness and efficacy of teaching and learning advanced networking protocols and their execution using the proposed TUI framework. To exploit and investigate the framework's abilities, the highly complex and abstract protocol of Open Shortest Path First (OSPF) was selected as the base implementation for this study. This communication and interaction protocol is considered as one of the most deployed routing protocols in computer networks and consistently presents a challenging aspect for both students and lecturers alike to explain and understand (Stanislaw *et al.*, 2016).

The proposed framework incorporates the TUI tabletop architecture designed and detailed in chapter 4, which couples the MCRpd interaction model (Ishii, 2008a) together with the reacTIVision computer-vision toolkit (Kaltenbrunner and Bencina, 2007a). Engagement with the proposed system was designed to be fully embodied within the physical domain using a set of dedicated 3D objects. This enabled students to interact with and provided input to the TUI system by manipulating these devices on the interactive tabletop and subsequently this provided control on the design, configuration and execution of a network topology.

Selection of the physical devices was undertaken with the intended aim to exploit the already existing familiarity of technical students with networking components. Thus, the representation of network components was achieved by making direct use of actual networking devices, captured in Figure 5.1, since these elements benefited from an intrinsic assimilation by the students and could be easily related to their technical foundations. In addition, this would intrinsically allow students to associate with each tangible component a set of features and functionalities which are typical of the represented device.

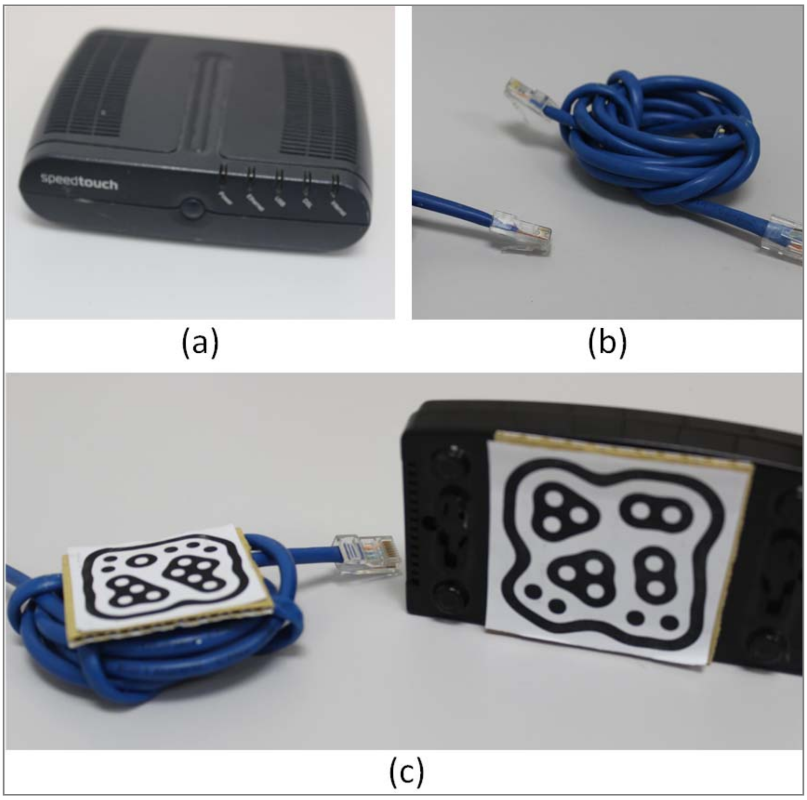


Figure 5.1: Tangible objects used to represent different networking components:

(a) Active Device - Router,

(b) Passive Device - Ethernet cable,

(c) reacTIVision 'amoeba' fiducials attached beneath tangibles (Kaltenbrunner and Bencina, 2007a).

To address the physical constraint of constructing complex topologies involving multiple units on the interactive tabletop area as well as to facilitate the recognition of objects by inexperienced students, simplistic and relatively cheap versions of network devices were selected for use within the system. Compared to their industrial counterparts, these networking devices are more commonly found within household environments and are manufactured physically in significantly smaller sizes than rack-mounted network units.

The following descriptions provide details of the individual devices:

- Router – A Thomson Speedtouch ST516, shown in Figure 5.1(a) was used to represent the routing function of a Layer 3 network device running the OSPF protocol.
- Switch – An Eminent EM4410 5-port switch was used to represent layer 2 devices that provide the interlink of routers in a multicast network
- Ethernet Cable – A Cat5e network cable, crimped with RJ45 connectors was used to represent connecting links between networking devices, as exemplified in Figure 5.1(b).

Attached underneath each representative object was a scaled image from the reacTIVision "amoeba" fiducials (Kaltenbrunner & Bencina 2007) as captured in Figure 5.1c. These high-contrast unique patterns are orthogonally optimized for identification using the installed optical camera. Furthermore, the computer-vision toolkit provides the ability to detect and discriminate each component using a numerical identifier, the centre point spatial location as well as the rotational angle respectively. Thus, this setup provides the framework with the ability to accurately track the spatial positions of all the used devices concurrently.

The intrinsic interlink between the physical and digital realms provided by the TUI framework affords students to physically construct the system through a hardware-based network topology as shown in Figure 5.2(a). Concomitantly with this interaction, the framework reflects this setup in the digital environment, Figure 5.2(b), whereby the network functionality would be additionally reflected and computed.

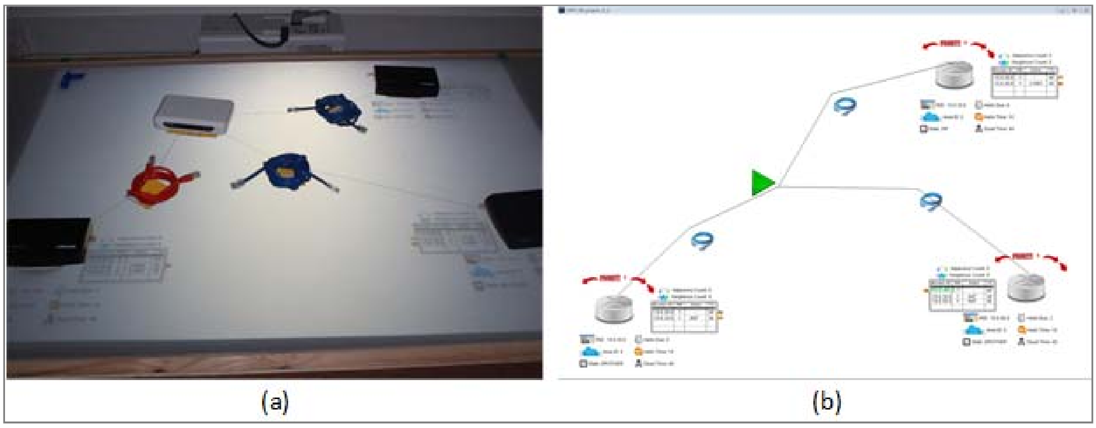


Figure 5.2: Simultaneously configured network topologies within the:
(a) Physical domain, and,
(b) Digital domain.

From an interaction perspective, the proposed framework offers users numerous interaction patterns for students to engage with on the system. These physical manipulations allow for individually distinct inputs to be provided to the underlying digital model, thus enabling students with a higher degree to control and configuration of the set topology. The domains of interaction made available by the TUI system are briefly described;

- Placement – The detection of tangible devices triggers the system to acknowledge the introduction of a new component in the networking topology. This action is equivalent to powering on devices within a network.
- Removal – The subtraction of a previously present tangible object from the system triggers the system to acknowledge the removal of a networking device from the topology. This relates in networking to a faulty device which will be excluded from the network and eventually cause a topological restructure.
- Proximal – Movement of objects around the interactive surface elicits different behaviour on the network when distinct devices are brought near each other. When intersecting the radial distance of an active device such as a router or switch with a cable element, the system establishes a

digital connection without the need to physically interlink these devices, hence enabling a more dynamic and experimental topology construction.

- Rotational – The physical rotation of devices is used to set the configurational parameters of the active devices. In particular, the priority parameter of each router is altered from its default value in this manner, whilst rotating the switch alters the protocol's execution speed. Rotating clockwise or anti-clockwise each device represents the feature of increasing or decreasing the respective parameter accordingly.

An inherent strength of the proposed TUI system is the intrinsic ability to augment physical devices with interweaved digital information. This setup employs a direct perceptual coupling approach whereby visual data is projected onto the table's surface top where physical interaction is occurring. Spatially allocating information near physical devices provides embodiment to the actual device. This embodiment is further solidified by the dynamic nature of the Graphical User Interface (GUI) which instantly reacts to the received physical input by altering the projected data on the affected device. This element of direct feedback provides computational coupling between the tangible input and underlying digital model of the proposed framework. The latter is achieved using a variety of GUI options, such as changing the nature of the information that is provided, altering the colour or even highlight certain data to natively influence the user's attention.

The development of the GUI interface together with the system's behaviour algorithms have been coded in Java. This architecturally neutral language was able to interface with the reacTIVision software libraries (Kaltenbrunner, 2009) that handle fiducial recognition of the tangible objects whilst supporting object-oriented programming to be developed. The software further constantly tracked the devices on the interactive tabletop and dynamically loaded and displayed a set of images in the correct location to indicate appropriate information embodiment on each tangible device. Apart from static displaying of data, the developed algorithm was also able to execute time-based animation of sequential images hence enabling the framework to simulate data sharing between employed devices.

5.2.3 OSPF using TUI Interaction

As an educational technology, the proposed TUI framework enables a series of activities to be undertaken by students whilst setting up and configuring their network topology. These interactions are digitally augmented with intermittent digital responses from the underlying algorithm that reflect the effect of the students' actions. Employing the tangible objects photographed in Figure 5.1, the working area is animatedly altered once tangible interaction is commenced on the TUI framework and representative digital symbols are projected underneath recognized devices to provide visual feedback.

Additional information, as illustrated in Figure 5.3(a), is further displayed upon detection of each router. This is augmentation provides students with the ability to understand the individual routers responsibilities when executing the intended OSPF algorithm on the network design. The complexity of the implemented protocol partially stems from the fact that numerous parameters play a relevant and dynamic role within its execution. This demands students to be consistently aware of, and understand, the altering values within each networking component. To minimize the characteristic overload of data and facilitate the understanding of the different values by students, a number of representative iconic graphical images are used to associate data as shown in Figure 5.3(b). These are then accompanied by device-specific sets of information which display the critical device details that are used by the protocol during its execution. Furthermore, the system also animates curved-arrow indications in the adjacent proximity of the router's priority value. This visual cue indicates to the user the ability to rotate the tangible device and subtly aids the user's interaction. As seen in Figure 5.3(c), this physical motion translates to a configuration of the priority attribute of the device, which has a direct implication on the OSPF protocol execution.

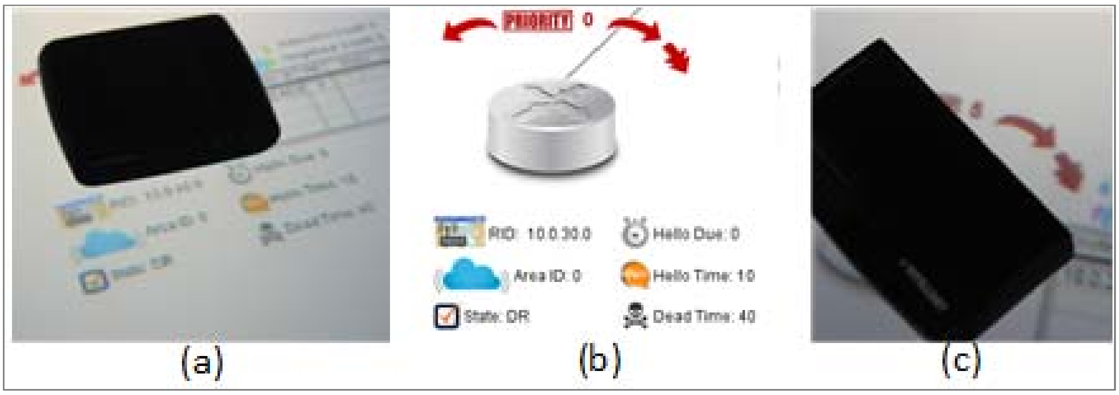


Figure 5.3: Embodiment of digital information on tangible objects;

a) Router specific data pertaining to the represented tangible device.

b) Simplified association and understanding of device parameters using iconic images.

c) Priority parameter on device altered via physical rotation.

The GUI is also used to represent the virtual connection established by the networking devices whilst constructing the network topology. Following the introduction of a physical Ethernet cable in the vicinity of an active device, the TUI framework established digital connectivity and this is represented by a vertex as shown in Figure 5.4.

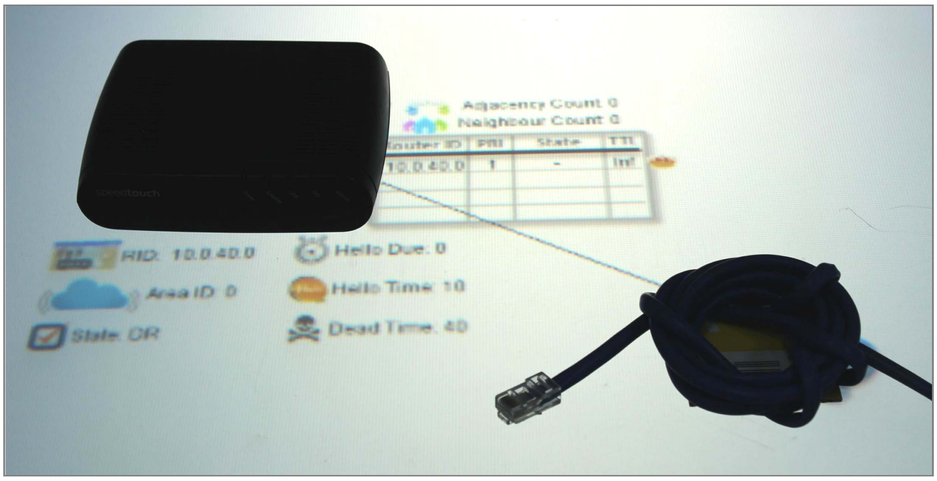


Figure 5.4: Virtual topological connections being established by the framework on the proxemic interaction of cables with networking devices.

Once connection of a device is established on a multicast network, the proposed system further augments students' abilities to understand the underlying operations of the OSPF protocol by visualising next to each router internal data tables. These routing and topology tables, illustrated in Figure 5.5, form an intrinsic part of the protocol’s operation and eventually determine the logical outcome of the network. In direct contrast from industrial software, the compilation and altering of these data tables are clearly highlighted by the proposed TUI system thus enabling students to grasp the underlying protocol’s dynamics.

Figure 5.5: Topological tables virtually embodied with physical router illustrate internal data held by the device for OSPF execution.

The exchange of data packets between OSPF devices is further visualised by means of appropriate digital animations within the proposed TUI framework. Following the elapse of device-specific protocol timers, the TUI framework symbolises the exchange of hello packets by sequentially loading an envelope image, visualised in Figure 5.6(a), from the source device towards the intended recipients. At the destination of this packet, the developed algorithm furthers students’ understanding by visually ‘opening’ the data packet to reveal the information held within. The contents of this packet, illustrated in Figure 5.6(b), are further accompanied by similar thumbnail images, as defined within router parameters in Figure 5.3, thus allowing pupils to immediately compare respective data values.

Figure 5.6: OSPF Protocol data transmission visualising:

a) Data exchange animation movement of a 'hello' packet transfer.

b) Information within the packet is exposed at destination device for analysis of the contained values.

The algorithmic processes that OSPF devices undertake upon receipt of a 'hello' packet are also animated using the TUI framework. This is done via a visual sequential comparison process, within which important data is highlighted by altering its size and colour, as captured in Figure 5.7(a). Using this approach allows students to understand better the internal execution of the network devices and hence be able to directly analyse the effects of the received data on the respective router. Moreover, the framework further directs the student's attention towards the protocol execution held within each networking device once the topological tables are compiled. This is achieved using a series of images to indicate the undertaking of an 'election' process by the device as seen in Figure 5.7(b). Understanding of the result is also assimilated by indicating on the resulting outcome table, adequate crown-based thumbnails to represent the elected designated router and backup designated router respectively as seen in Figure 5.5(b).

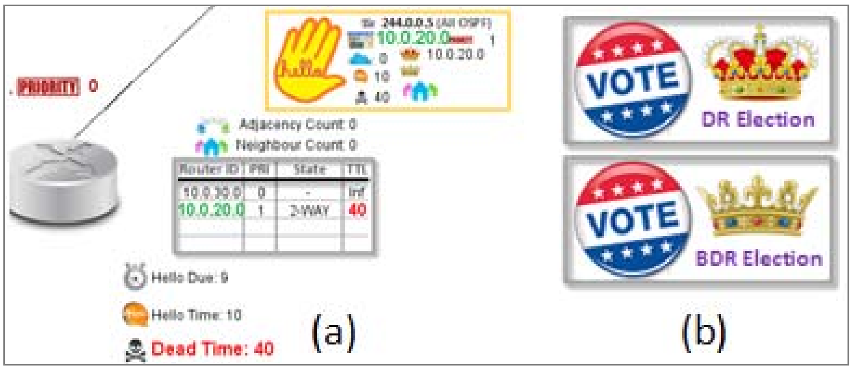


Figure 5.7: Information visualisation during router election process

a) Highlighted information comparison between the current and newly received packet data.

b) Election images used to signal internal router processes.

By means of this digital projection, the proposed TUI framework is able to intertwine the virtual simulation of the network together with the physical devices. This setup allows users to appreciate in visual detail the protocol's processes, as well as enables the direct manipulation of critical device parameters such as priority value as shown in Figure 5.3(c). This amalgamation hence provides a unique ability to visualise and interact with the abstract and computationally complex notions of a networking protocol.

5.2.4 Experimental Results and Discussion

The proposed TUI system was implemented for evaluation at Middlesex University Malta within the undergraduate degree in Computer Networks. Final year students reading a module in advanced network design were chosen for the evaluation during one of their scheduled lectures. These candidates all had a good knowledge of networking devices and a basic understanding of networking protocols, attained mainly throughout the previous lectures of the same programme. The delivery of the OSPF protocol formed a threshold concept within the remaining syllabus of the specific module, and the evaluation exercise was timed to concur with the scheduled delivery of the session.

5.2.4.1 Evaluation Methodology

Student selection was based on a purposive sampling technique, and a class composed of 25 students within the age of 19 to 31 was chosen for evaluation. Students attending the aforementioned class were enrolled for their study in either full-time or part-time mode at the university. Apart from generally resulting in an age discrepancy, this disparity also presented a potential variation in the exposure and practical experience of students towards the subject of computer networks gained mainly within industry contexts. To mitigate this potentially biasing factor, all students were subjected to an a priori examination prior to their tuition session. As shown in Appendix B.1.1, this time-bound assessment consisted of ten (10) open-ended questions relating directly to the technical knowledge and theoretical details within the OSPF protocol's election process and served to derive an individualistic baseline on the subject-specific knowledge for each student.

Students were not forewarned about the upcoming research study and following their pre-test completion, a random splitting selection was undertaken so that twelve (12) students were chosen for inclusion within the experimental group, whilst the remaining 13 candidates would constitute the evaluation's control group. The latter group would be introduced to the OSPF protocol using the traditional lecturing approach, involving access to a PC lab and smartboard technology in addition to the standard overhead projection. In contrast, the experimental group would undertake the explanation of the same projected slides making use of the proposed TUI system. To ensure coherent experimental conditions, both lecturing sessions were carried out within the same lecture timeslot, for a predetermined fixed duration and covering the same technical content using an identical set of lecture slides.

Upon completion of each respective session, both groups of students were provided with another examination script, shown in Appendix B.1.2, containing a further ten (10) open-ended questions. The latter test assessed the same theoretical understandings of the a priori test yet made use of different questions and structure to ensure no cross-contamination between examinations. Scripts from both sessions were marked by the same lecturing academic in line with a precompiled marking scheme so as to ensure a fair and consistent assessment grading on the open-ended questions asked. This evaluation methodology was thus designed to provide a quantitative appraisal on the variance in academic achievement obtained by students within their answers. This equitable analysis would hence yield the necessary data to objectively evaluate the aptness and efficacy of employing a TUI framework for teaching and learning abstract principles in computer networks.

5.2.4.2 Results and Discussion

The pre-test bar graphs depicted in grey within Figure 5.8 represent the individual scores obtained by each student during their a priori examination. Whilst the mean score for pre-tests in Figure 5.8(a) was 31.3% (SD: 11.4) and that of Figure 5.8(b) was 28.6% (SD: 7.7), no statistical significance was present in the results ($\rho > 0.5$) when analysed using a comparative means t-test. This highlighted the fact that the random selection strategy employed whilst segmenting students was appropriate and did not include any knowledge bias.

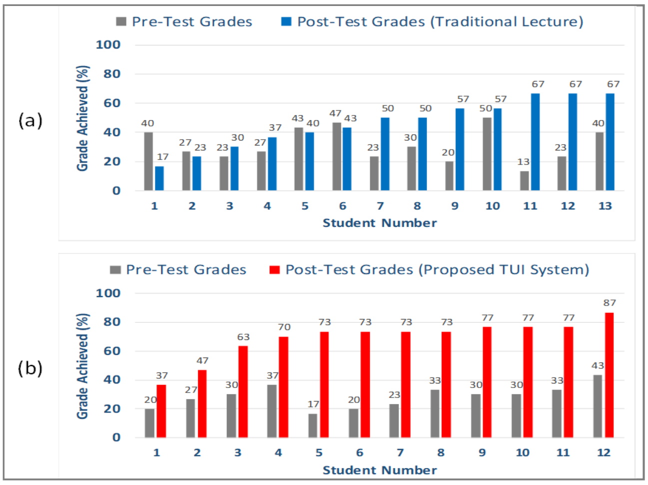


Figure 5.8: Comparison of individualistic student assessment grades obtained before and after:
a) Attending a traditional lecture session on OSPF.
b) using the proposed TUI OSPF Framework.

Separately, the coloured bar graphs within Figure 5.8 highlight the marks attained by the same students during the second assessment. This followed the teaching intervention undertaken by each group and hence represents a direct comparison between traditional educational technologies and the proposed TUI framework on their respective effectiveness for conveying knowledge about OSPF protocol operation. The comparative histograms in Figure 5.8(a) illustrate that following attendance to a traditional lecture, students enhanced their average understanding of OSPF to a resultant average group mark of 46.5% (SD: 16.7). The resulting data was further analysed on an individualistic basis through the comparison of every student's pre-test and post-test performance by means of a paired sample means t-test. This statistical approach illustrates that students in the lecture-based control group yielded a statistically significant, at ($\rho < 0.05$), mean increase in OSPF knowledge gain of 15.3% (SD: 21.8) with respect to their individual pre-test results.

Whilst these results illustrate that the conventional lecture-based approach could positively introduce students to the concept of OSPF election protocol, the success of this approach is paled in comparison to the results achieved by students using the experimental TUI framework. As illustrated within the comparative histograms in Figure 5.8(b), students in the experimental group improved their group average from 28.6% (SD: 7.7) to 68.9% (SD: 13.9). This achievement was analysed using a similar paired sample t-test analysis on the attained grades, which statistically confirmed that students within the group individualistically obtained an average grade increase of 40.3% (SD 12.2) on their post-test assessments following the TUI evaluation session. This difference between the initial and final results was established at ($\rho < 0.001$), further underlining the statistical significance of the obtained results using the proposed TUI framework.

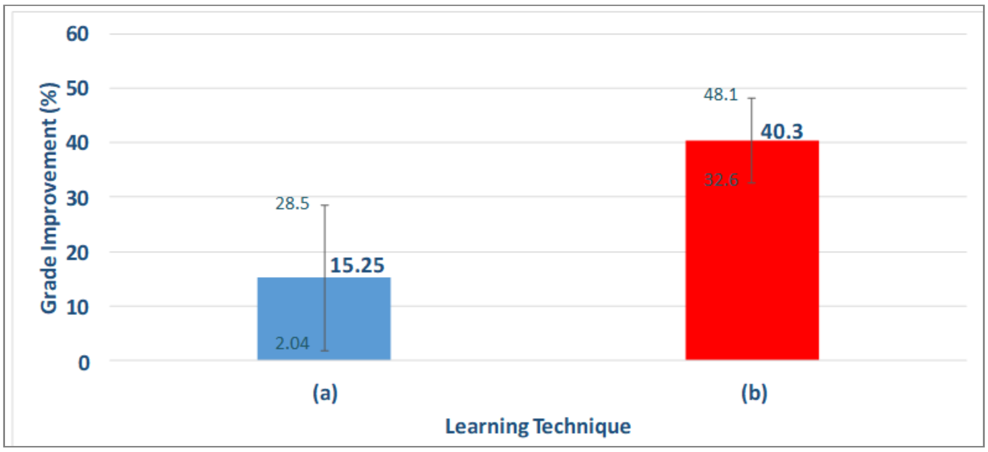


Figure 5.9: Knowledge gain obtained by students in each group at 95% confidence bounds:

a) after attending a traditional lecture session on OSPF.

b) after using the proposed TUI OSPF Framework

The diagram in Figure 5.9 further analysis the results obtained by depicting the mean aggregated difference of individualistic students according to the attended session. These results are further elaborated with the diagrammatical representation of the respective 95% confidence lower and upper bounds for grade improvement registered by each lecturing technique. The individualistic differences obtained by each student within the two assessments were further analysed using an independent sample t-test. This result confirmed that the proposed technique is able to attain 24.9% (SD: 7.1) higher knowledge gain with respect to traditional educational technologies. This result was achieved at a statistical significance of ($\rho < 0.001$), and analysed under Levene's test affirmation for homogeneity of population variance.

5.3 Database Normalisation Processes

The use of educational technology for teaching computer database related concepts has been inherently ingrained within the evolvement and popularisation of the technology (Lewis, Bernstein and Kifer, 2002; Mitrovic, 2012). As GUI interfaces for database management systems (DBMS) became evermore interactive, educators employed these software solutions more effectively in the classroom leading to a relative shortage of dedicated educational tools for complex databases (Mitrovic *et al.*, 2004). Educational developments in literature, in fact limit to Web-based simulators such as; *ADVICE* (Cvetanovic *et al.*, 2011), *SQL-Tutor* (Mitrovic, 1998a, 1998b, 2001; Mitrovic and Ohlsson, 1999), *RDBNorma* (Dongare, Dhabe and Deshmukh, 2011), *KERMIT* (Suraweera and Mitrovic, 2002) and *NORMIT* (Mitrovic, 2002). These educational software packages differed mainly from commercial applications by providing a more simplified and assisted setup of GUI based databases aiming to target and facilitate database development to inexperienced users (Mitrovic, 2005, 2012; Ram, 2008).

The abstract and complex domain of database analysis and design however commonly poses a threshold concept for academics to explain, often leading to disappointing delivery of learning outcomes to students who do not grasp the concept via GUI interaction (Czenky, 2014). The experienced teaching difficulties of fundamental database concepts such as normalisation have been expressed by Connolly and Begg (2006) who argued for the effective need for embedded problem-solving contexts in the modern tuition for information system design.

5.3.1 Normalisation TUI Framework

In view of the restricted educational technology options investigated in the domain of databases, and in mitigation to the current limitations noted within TUI and active learning literature, the proposed TUI framework was designed so as to present students with the ability to interactively manipulate and visualise the abstracted concept of database normalisation. Specifically, students were enabled to interact with the various database and table attributes during the different stages of the normalisation sequential processes whilst at their own learning pace visualise the underlying principles being adopted throughout each stage.

The proposed framework utilises the TUI tabletop architecture, designed in chapter 4, upon which the MCRpd interaction model (Ishii 2008) and ReacTIVision framework (Kaltenbrunner & Bencina 2007) are integrated. This architectural model enabled the proposed TUI framework to provide a perceptually coupled tabletop interactive surface upon which students are able to visualise and interact with educational concepts whilst retrieving direct and localised system feedback. Furthering current implementations, the TUI framework further proposes the integration of audio together with visual and haptic feedback, to further the immersive experience provided in the HEI context.

The physical interactive engagement of students with the proposed framework was achieved via the manipulation of dedicated 3D objects. These physical components were aptly selected to represent concrete real-world models and thus embody the various attributes qualities of data fields used in the problem-based database context. Thus, the selection of the contextual scenario and respective physical objects were therefore sourced from familiar student environments so as to represent an inherent understanding of their meaning and association. This provided students with the ability to further focus on the normalisation task without needing to decode or shift attention towards the utilising the computer interface and its representation.

In order to aid further the assimilation of data, a university programme transcript was considered as the database scenario for engaging with in exemplifying normalisation. Apart from reflecting commonly used attributes and inherently familiar data for undergraduate students, this domain further enabled the creation of evermore relatable tangible devices as described for Figure 5.10(a-d). This strong embodied cognition supported a more engaging interaction with the abstracted data fields as well as an augmented focus on interacting with the described normalisation processes.

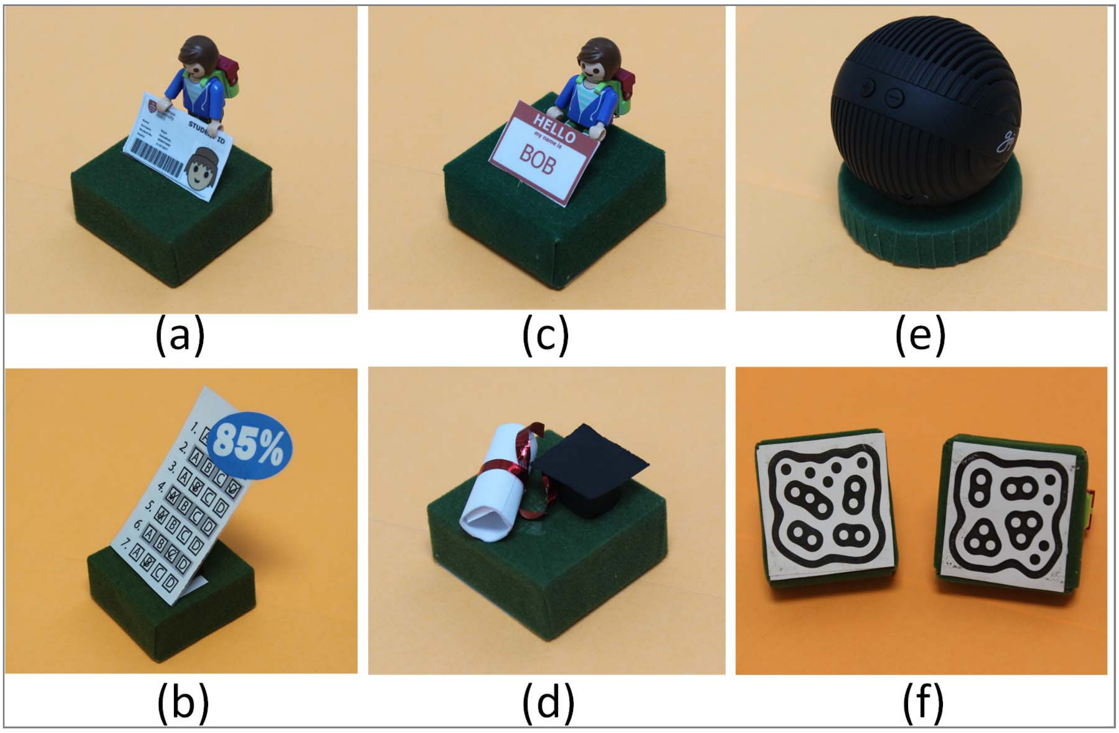


Figure 5.10 Tangible objects representing the attribute fields of selected database:

a) Student ID - Small figurine holding university identification card,

b) Grade Achieved – Corrected multiple choice questionnaire with score,

c) Student Name – Small figurine holding nametag,

d) Degree Programme – Miniature graduation cap and certificate scroll,

e) Setup Controller – Rotatable speaker with Bluetooth® connectivity,

f) Tangible objects underside – ReacTIVision ‘amoeba’ fiducial symbols.

As shown in Figure 5.10, each object was mounted on a wooden platform (6cm x 6cm) onto which a reacTIVision ‘amoeba’ fiducial was attached (Bencina and Kaltenbrunner, 2005) as captured in Figure 5.10(f). The dimensions of tangible devices were designed to enhance the usability and comfortable interaction for students, whilst at the same time occupying a minimal spatial area on the interface so that to maximise space for virtual projected data. The reacTIVision ‘amoeba’ symbols, specifically designed with inter-symbol orthogonality, further assisted the system camera to locate and identify each object on the interactive surface. This enabled multiple objects to be used in conjunction, whilst providing the user with the ability to spatially drag the components on different areas of the screen.

In line with the developed physical architecture, the TUI framework interweaves the digital domain by means of a dedicated software component. The latter was responsible for embedding the necessary concepts of database normalisation which the students would be interactively engaging with. Furthermore, these digital elements aid the TUI system to augment and interlace information on the tangible objects via dynamically projected data, hence providing students with the ability to associate and constructively manipulate physical objects.

The Graphical User Interface (GUI) of the system was developed on the Unity™ gaming engine platform using the C# programming language. As portrayed in several screenshots within Figure 5.11, the projected digital interface makes use of a number of graphical components to provide the student with the necessary ability to undertake the different conceptual alternations at each stage of normalisation technique. GUI and visualisation cues are thus aptly employed to aid students in understanding their current stage-related task as well as receive visual feedback on their interactions. The digital interface, as captured in Figure 5.11(a-d) makes use of graphical placeholders to assist students in understanding the physical movements expected at each normalisation stage. These are accompanied by virtual messages that instruct the student on the TUI operation and database normalisation-related tasks. This provides the TUI framework with the capability to differentiate between two visual data presentations and thus embed a more immersive interface. Static data visualisations are thus focused mostly on relating instructional information about the current normalisation stage aspects and thus providing the ability for students to recall contextual information. Conversely dynamically changing messages and graphics strategically divert user attention to the operations being performed by interaction with the TUI framework.

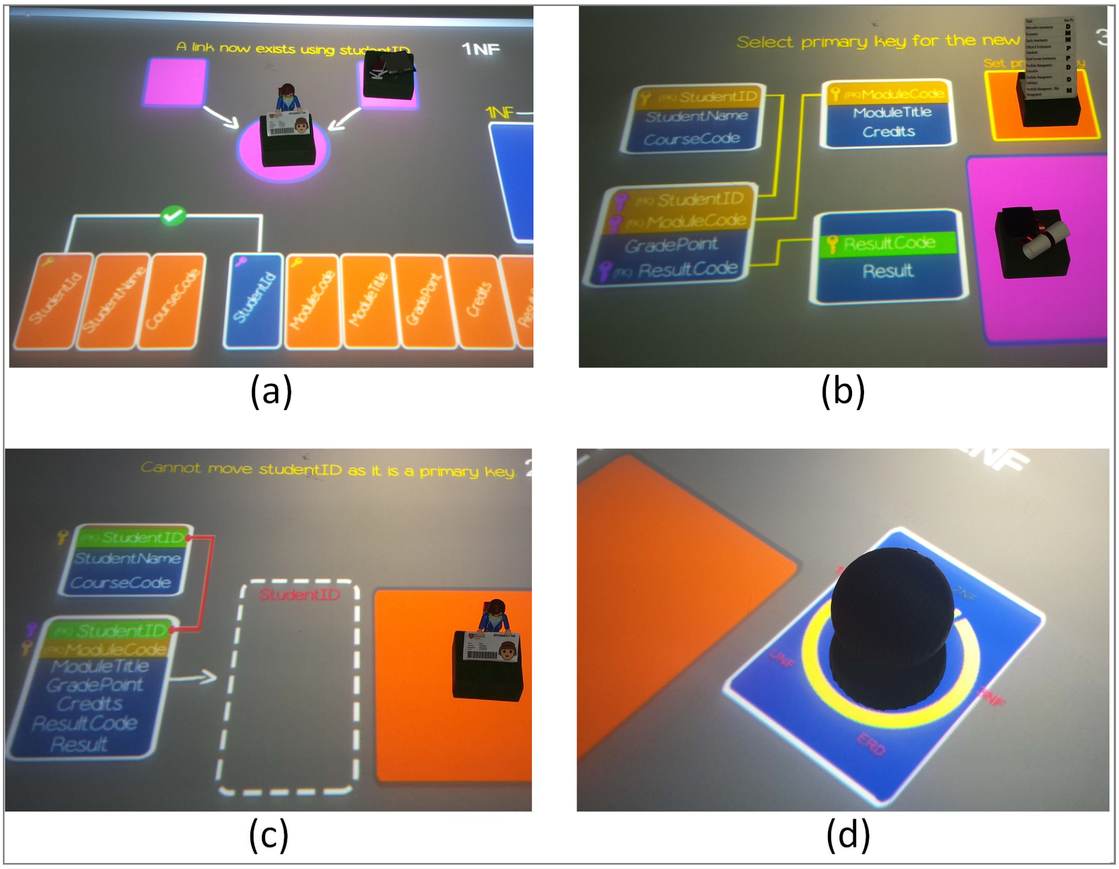


Figure 5.11 GUI screenshots of proposed TUI system [2]:

a-c) Different instructions provided to students in order to progress through the processes and concepts of normalisation with various placeholders and visual cues dynamically displayed,

d) Setup Controller – Projected information prompting the user to rotate the tangible object so as to change normalisation stages adjacently displayed.

[2] Video clips of Normalisation TUI framework available on https://youtu.be/bC8Rbi1sRhQ

The illustrated GUIs in Figure 5.11 automatically change a subtly integrated component colour scheme (from orange to purple) throughout the procedural execution. This consistent and coherent associate through interaction allows the user to interpret feedback instinctively when a tangible object has been correctly placed and/or identified by the system. Furthermore, a number of dynamic links, arrows, and messages as illustrated in Figure 5.11(a-c) are presented by the system providing users with a pervasive interaction engagement as well as divert attentive focus on visualising the underlying processes occurring.

Additionally, the proposed TUI framework integrates the use of a further distinct feedback channel through the embodiment of audio. This is integrated within the ‘setup controller’ tangible devices, shown in Figure 5.10(e) and Figure 5.11(d). This device is able to provide additional information and instructions to students via the internal speaker which communicates through Bluetooth® protocol. This immersive channel allows the system to dynamically trigger the playback of appropriate voice messages and notification sounds, providing the user additional instruction and feedback on the respective stages of the normalisation system. Incorporating and carefully integrating these interactive approaches, hence provides the TUI framework with the ability to gain a substantial cognitive and social advantage for students. It also allows a more engaging teaching and learning activity whilst allowing students to explore, assimilate and express their knowledge better on the abstracted concept.

5.3.2 Evaluation in HEI context

The proposed TUI framework was evaluated via deployment within undergraduate degree programmes of Computer Science and Information Technology at Middlesex University Malta. The identified normalisation process forms the principal threshold concept which needs to be quickly captured by students within this comprehensive module on databases. Unfortunately, this concept is commonly perceived as a particularly difficult topic to teach and learn, from both students and lecturers alike, and inadequate understanding often hinders students' progress on the domain. To this end, once the TUI framework was assembled, programmed, and implemented as described in the previous section, the evaluation of the innovative TUI practice was scheduled within the course to integrate naturally within the academic curriculum structure.

5.3.2.1 Evaluation Methodology

To quantitatively assess the suitability and effectiveness of the proposed TUI framework, the evaluation methodology illustrated in Figure 5.12 was adapted during this study.

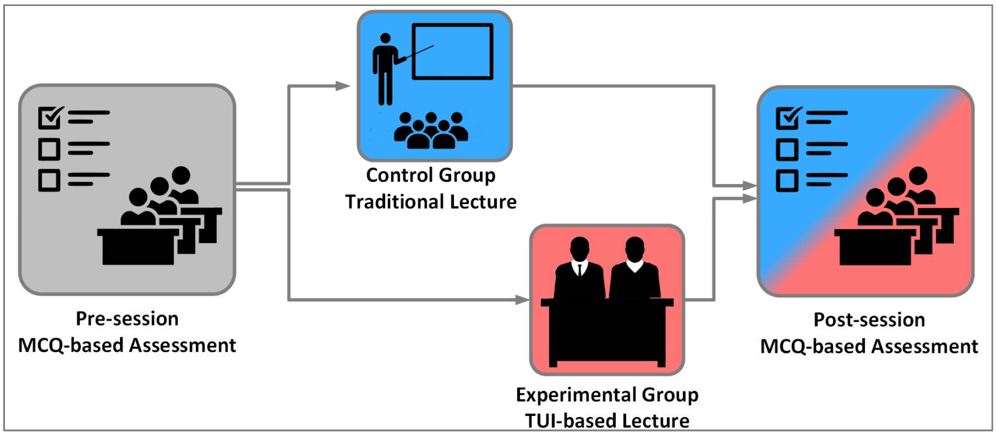


Figure 5.12 Evaluation stages designed for implementation within an HEI context.

The evaluation methodology was conducted with 16 second-year students, who were all enrolled in this course and were selected based on a purposive sampling technique. To establish an a priori baseline of student knowledge before the evaluation session, a multiple-choice questionnaire (MCQ) was provided to students so as to test their former knowledge on the subject. Following this test, the class was randomly split such that seven (7) students would serve as a control group, whilst the remaining nine (9) students formed the experimental group. The former would undergo a traditional tuition session whereby normalisation was exemplified and explained using a traditional educational technology such as smartboard, projected slides, and whiteboard setup. Subsequently and separately, the experimental group was on the other-hand introduced to the concept of database normalisation using the proposed TUI system by the same lecturer as illustrated in Figure 5.13.

Figure 5.13 Evaluation session of the proposed TUI framework for database normalisation concepts

The teaching and learning effectiveness of the proposed TUI system was evaluated using both summative and formative techniques. A diverse set of questions was specifically designed to audit the ability of students to answer both theoretical and practical aspects on the concept of normalisation whilst a number of probing questions were posed to derive a more formative assessment of the TUI framework.

5.3.2.2 Summative Appraisal

Following the teaching sessions on database normalisation using either the TUI framework or traditional lecturing, both cohorts of participants were subjected to a second different multiple-choice questionnaire, shown in Appendix B.2.1, re-examining their acquired knowledge on the identical concepts covered within either session yet adopting a different set of questions to mitigate potential bias between assessments. These post-test results have been compiled for both teaching methodologies respectively and illustrated in Figure 5.14(a) adjacent to the respective pre-test scores achieved by the same students.

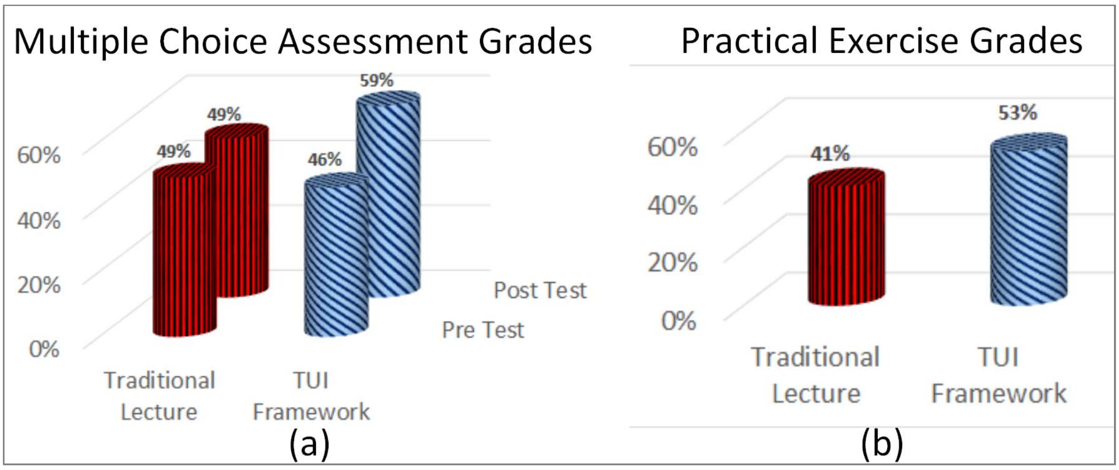


Figure 5.14 Comparative analysis of grades achieved in:

a) Theoretical multiple-choice assessment

b) Practical case-based exercise.

As can be derived from the comparative analysis of the results in Figure 5.14(a), students who were exposed to the concept of database normalisation using the proposed TUI framework were able to achieve a result grade improvement of 13% (SD 22.3) with respect to their traditional lecture counterparts at a 90% confidence interval. This result was obtained via an independent means t-test on the individualistic knowledge gain between MCQ assessments of each student within either group. Another assessment administered a problem-based query to students following their respective learning session which aimed to assess their ability to employ the learned normalisation concepts within a practical database scenario. To this end, a data-table containing some unseen information, exemplified in Appendix B.2.2, was provided to students who were individually asked to normalise and design a relational database diagram based on the concepts explained during the lecturing session. The results, represented in Figure 5.14(b), highlight that students were able to utilise and adapt their knowledge better after interacting with the proposed TUI framework. These outlines, the potential ability of tangible interfaces to provide a deeper understanding and learning of abstract concepts with HEI contexts.

5.3.2.3 Formative Appraisal

The positive achievement registered from the summative assessment was further collaborated via the formative feedback derived from students. Participants in the TUI demonstration highlighted that the interactive aspect of the system provided an opportunity to engage and experiment with the various stages of normalizing data. A process which was also referred to as enjoyable. Furthermore, it was commonly noted that the innovative audio and visual integrated feedback allowed students to understand better the tasks being undertaken and the respective concepts at each normalisation stage.

From a lecturing perspective, the system furthered the ability to explain and illustrate to students the different aspects of database normalisation. Moreover, the TUI system allowed for an interactive session in which students were able to express their knowledge and collaborate together in deriving the correct task processes. This inherently provided the ability to assess the individual understanding of students and deliver formative feedback instantly on the subject.

5.4 Queuing Theory Computation

Within the disciplines of Science, Technology, Engineering and Mathematics (STEM) a solid introduction to queueing theory has long served as a staple foundation for the eventual introduction to computer modelling and simulation modules (Grossman, 1999; Mei and Cheng, 2013). Albeit being entrenched within the realm of probability theory, however, the applicability of queueing theory is far-reaching and thus is frequently encountered also within business-school courses such as management science and operations research (Liberatore and Nydick, 1999). This diverse audience commonly exposes the problem in which students, with a weak understanding of mathematics and probability, struggle to grasp the elementary stochastic aspects of this theory and hence fail to obtain the fundamental elements of this concept (Perdos, Chatzigeorgiou and Stephanides, 2004).

As a means to avoid spending an inordinate amount of time explaining the mathematical aspects of queuing theory (Deng and Purvis, 2015), educators commonly resort to the use of computer simulations to accommodate the students' diversity in prerequisite knowledge (Reed, 1980; Bedwell, Hancell and Callus, 1984). The instructional delivery of queuing theory using computer-based technology has been well discussed in literature (Reed, 1980; Ernesto, 2002; Goldsman, 2007; García and Hernandez, 2010; Mandelbaum and Zeltyn, 2010) with notable success reported for bridging the cognitive gap in student cohorts (Fitzgerald and Place, 1995; Ang, 2010). This has been achieved in Higher Educational Institutions (HEIs) via both a repertoire of dedicated simulation packages (Swain, 1997) or alternatively by the development of spreadsheet models. In particular, the latter allows the construction and utilization of worksheets and macros with minimal programming knowledge hence making them more appealing to less technically oriented students (Ragsdale, 2010).

Whilst the deployment of technology in such instances serves to attest to the effectiveness of information dissemination within teaching and learning (Rahman *et al.*, 2015), ensuring that proper insight is obtained by students on the underlying concept is more elusive (Grossman, 1999). This echoes the concern that unless the technology is properly and systematically employed within classrooms, the resultant effects would not align with aspired expectations (Alsafran and Brown, 2012; Laurillard, 2013). Hence, positive impact on teaching and learning using technology requires educators to explicitly take the aspects of content and pedagogy into account (Day and Foley, 2006; Rahman *et al.*, 2015).

This concern is critically present within engineering curricula whereby the understanding of queuing theory and simulation modelling provides a peculiarly intertwined dependency which cannot be overlooked (Chan, 2007). Although simulation is often emphasized as an alternate tool for queuing theory evaluation, skimming over the mathematical analysis and derivation of parameters results in a very limited apprehension of the complex system dynamics, which in turn, hinders the necessary conceptual understanding underpinning the modelling simulation (Bhat, 2014).

5.4.1 Queuing Theory TUI Framework

In view of the outlined vacuity within HEI education, this section presents a novel technological framework which directly aligns with the pedagogy of engineering education for the teaching and learning of queuing theory. The proposal presents the adaptation of a TUI framework to provide computer networks students with the ability to visualise, understand and interact with the underlying concepts of queuing theory. Central to the efficacy of this design methodology is the ingrained alignment with inquiry-based and active learning models, both of which advocate student interaction via experimental and collaborative learning at the core of their effectiveness (Chan, 2007; Psycharis, 2016). Thus, in stark contrast to the reviewed work in literature, the proposed framework capitalizes on the following tangible designed considerations in the development of an effective TUI educational framework;

- Conceptual understanding through active learning pedagogies in contrast to engaging HEI students as passive recipients to the delivery of knowledge.
- The embodiment of tangible relations and interactions within the queuing system entities, hence diminishing the perceived operational and cognitive complexity.
- Multimodal visualisation of the mathematical calculations and resultant effects of parameters changes which aid in exposing underlying system functionality and reduce conceptual uncertainty.
- Staged models of conceptual complexity, which provide students with the opportunity to understand more effectively the underlying computational aspects.
- Exposure to realistic and contextualised queuing theory examples which directly aid knowledge assimilation and interpretation.

5.4.1.1 System Overview

The proposed TUI framework designed was based on the *Model-Control-Representation (physical and digital)* (MCRpd) interaction model (Ullmer and Ishii, 2001) illustrated in Figure 5.15(a). This framework extends the Model-View-Control (MVC) typically used within GUI interfaces by separating the “view” component into tangible and intangible representations (Yuan, Yang and Xiao, 2007). The latter serves as a digital feedback to the user via video projection and/or sound, whilst the former component is tightly integrated to control elements and provides a tangible and physical representation of the system state.

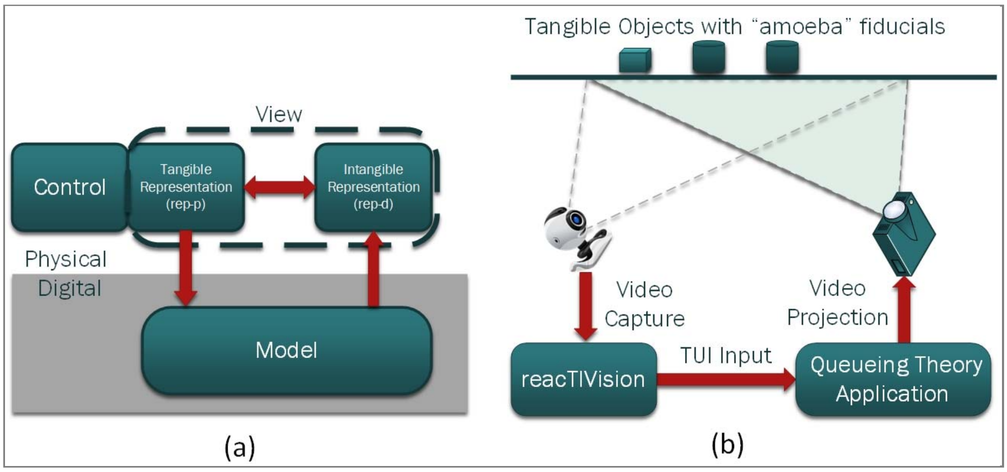


Figure 5.15 Design base models for proposed TUI framework:

a) MCRpd Interaction Model for TUI framework (adapted from Ullmer and Ishii (2001))

b) ReacTIVision architectural framework (adapted from Kaltenbrunner and Bencina (2007a)).

The functional model of the developed system was based on the reacTIVision optical tracking framework (Kaltenbrunner and Bencina, 2007a) depicted in Figure 5.15(b). This interactive tabletop architecture was selected based on its inherent ability to support collaborative experimentation whilst providing a clear understanding of the system functionality via both tangible and digital representations (Maquil and Ras, 2012). Thus, the proposed framework integrates the physical construction design of the TUI tabletop architecture detailed in chapter 4.

The amalgamation of these two frameworks is outlined within the sequence diagram in Figure 5.16. The model details the characteristics imparted by the MCRpd framework in which tangible objects optically tracked via reacTIVision fiducials are used to provide controlling inputs. Consequently, whilst embodying tangible interaction and manipulation, the queuing theory model conveys feedback to the user by altering the digital projections to provide perceptual and computation representation coupling.

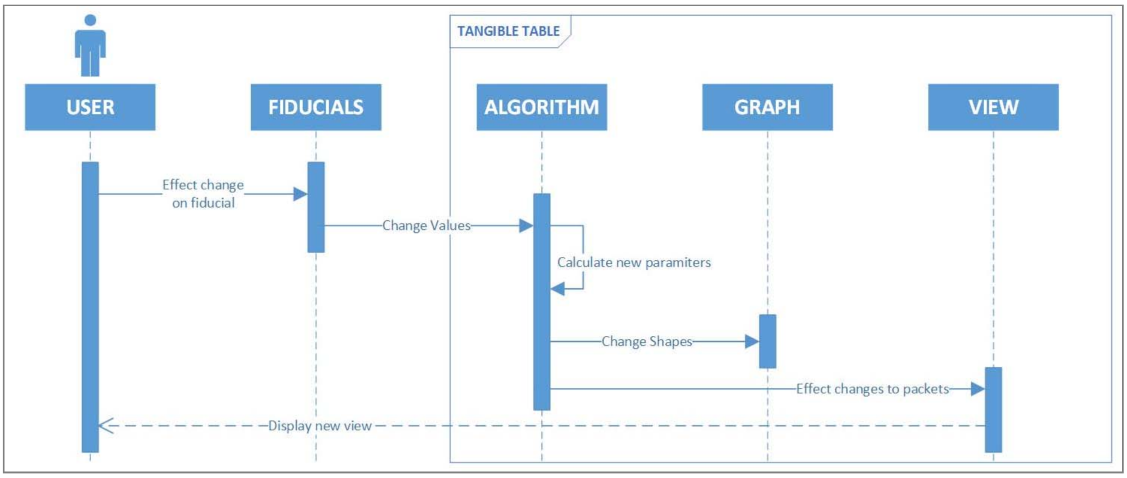


Figure 5.16 Sequence Diagram for the proposed TUI framework.

5.4.1.1 Tangible Interactions

Underlying the effectiveness of the proposed TUI framework is the designed ability for students to interactively engage with the queuing scenario using a set of tangible 3D objects. Manipulation of these physical representations thus affords the ability to alter configuration and computational parameters of queuing theory in real-time to constructively design conceptual models.

To integrate embodied cognition, the selection of tangible devices was undertaken with the intended aim to innately symbolise contextualised queuing system components and hence exploit the familiarity of students with these items. In line with a computer networks perspective, physical models such as routers, data buffers and servers were used as depicted in Figure 5.17(a). These capitalized from the intrinsic assimilation by computer network students who could easily relate entities to their technical foundations. Furthermore, students were able to associate each tangible component with a set of functionalities typical of the representative device, and thus aid in the understanding of the queuing system when learnt within a computer networking context.

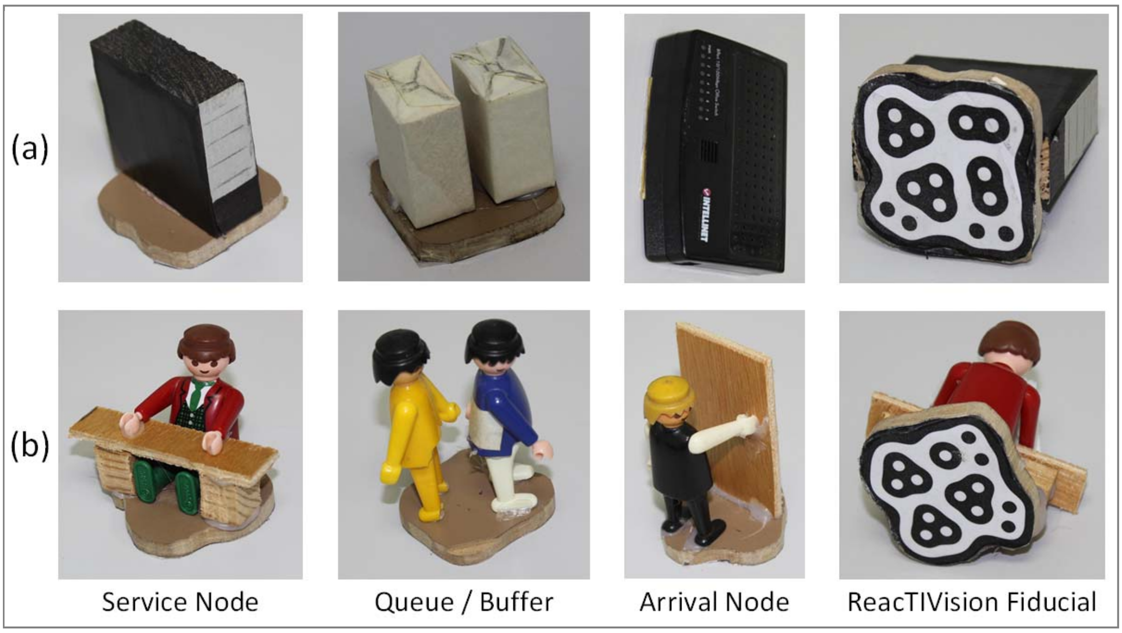


Figure 5.17 Design and selection of tangible objects representing arrival, buffer/queue and service tasks in a queuing model for;
a) Computer networks packet processing,
b) Client servicing business organisation.

Owing to the vast applicability of queuing theory with real-life experiences (Mei and Cheng, 2013) and to facilitate the understanding of the abstract concepts to non-technical students, the TUI framework was further adopted towards a commercial enterprise context. Taking advantage of the inherent flexibility and functionality of TUI systems, an alternate set of tangible objects were developed to represent an organizational queuing case scenario as illustrated in Figure 5.17(b). Human figurines from the Playmobil® toy sets were used to represent the various roles within a service firm queue. A set of figurines wearing formal attire were thus used to represent employees (advisors/servers) whilst an alternate set of casual wearing figurines represented clients either entering the queue system (opening a door) or waiting in line to be served (queue buffer).

Each tangible element was placed onto a wooden platform, which apart from providing mechanical stability also served to attach a scaled image of a reacTIVision "amoeba" fiducial (Bencina and Kaltenbrunner, 2005) as shown in Figure 5.17. These high-contrast symbols are orthogonally optimized for unique identification using the installed camera. This enables the developed TUI framework to detect, discriminate and locate the centre-point of each individual object used. Apart from affording the system with spatial object tracking, the employed “amoeba” symbols are also rotationally variant, thus allowing the identification of the rotational angle for each placed component on the interactive surface.

The proposed TUI system capitalized on these aspects by employing the interactive notions of object placement and rotation to impart different controls. Whilst sustained object presence detected the inclusion of an additional parameter or server within the system, the rotational angle of each object was directly linked to the respective entity attributes. Hence, this allowed the increase or decrease of input variables values for the queuing theory computations by physically rotating objects in clockwise or anti-clockwise directions. This computational coupling between physical and digital domains thus allowed the system to adapt the simulation parameters in real-time whilst aiding students to collaboratively experiment with queue’s attributes to understand the implicit interactions between each variable.

5.4.1.2 User Interface

The augmentation of tangible devices by interlacing physical aspects with digital information is one of the innate advantages conveyed by the proposed TUI system. This perceptual coupling is embedded through the TUI framework by visually projecting the system’s output onto the same interactive surface utilized for input control. The resultant spatial multiplexing provides the ability to embody digital information to the tangible devices, by projecting data spatially adjacent to the physical component. Moreover, the dynamic nature of the developed GUI is able to react instantly to the received physical input and hence provide positive feedback to the user via alteration of the projected view. This closed-loop element ensures computational coupling exists between the tangible input and the underlying digital model as modelled in "View" component of Figure 5.15(a).

In order to provide real-time implementation, the system's behaviour was implemented in Java which employed reacTIVision libraries for TUIO tracking (Kaltenbrunner *et al.*, 2005) and interfaced with JavaFX for graphics handling and animations. This combination allowed the proposed system to efficiently develop a variety of GUI options to alter the user's attention such as; data highlighting, colour alterations and dynamic information changes.

Upon programme initialisation, a GUI design of the proposed system is presented as illustrated in Figure 5.18. This projected visual interface is designed to spread along the entire interactive tabletop, which apart from aiding visibility allows for the clear designation of the four main segments highlighted in green within Figure 5.18. These areas are further laid out to provide a flow continuation of the queuing process in a clockwise movement as illustrated using red arrows between stages.

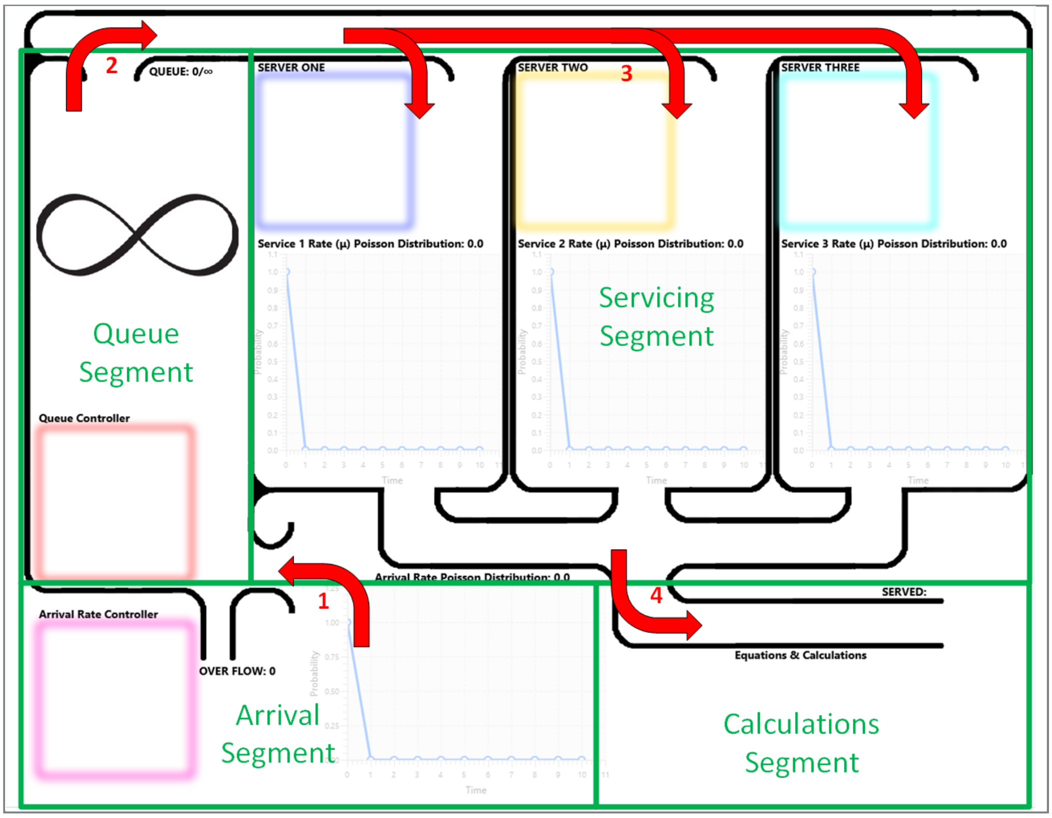


Figure 5.18 Initial GUI design segmented according to the distinct queue model areas with superimposed flow indicators [3].

Perceptual coupling was also utilised within the GUI element to subtly instruct students on the operation of the proposed TUI system. By means of coloured square placeholder sections, users were made aware of the ideal locations within which tangible objects should be placed. Moreover, these segments were dynamically highlighted during operation, as visualised in Figure 5.19(a), in order to attract user attention to the respective area as well as to provide localized indications to the required actions. Visual indicators were also employed by the system to indicate to students the available manipulations on each object. As depicted in Figure 5.19(b), this was achieved using four animating arrows which are displayed rotating in clockwise or anti-clockwise fashion adjacent to the recognized TUI objects.

---

[3] Video clips of Queuing TUI framework available on https://youtu.be/IX4TaEPCWQ8

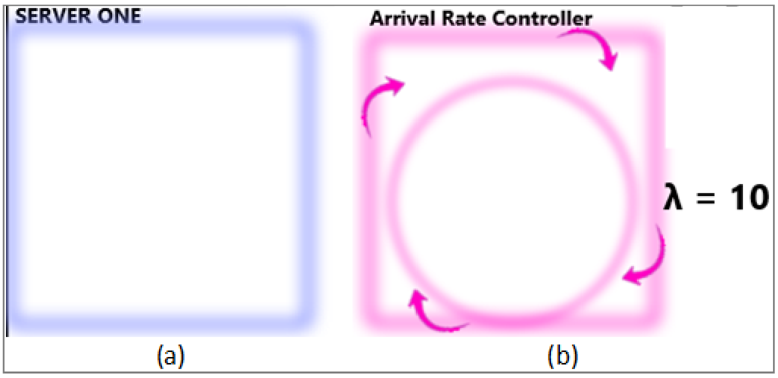


Figure 5.19 Graphical animations used in order to provide perceptual feedback to users on the TUI systems functionality.

5.4.1.3 Algorithmic Design

A prerequisite to understanding the conceptual operation of queuing theory is the ability for students to interpret the stochastic distributions on arrival and service rates, denoted by λ and μ respectively. This process presents an abstracted challenge to students since, although analysed and quantified statistically within Equation 4.1, precise prediction of the arrival/service pattern is not possible due to its inherent random nature at any given time. For a particular time occurrence *i* and with an arrival rate λ, the Poisson distribution can be characterized as;

$$p(i, \lambda) = \frac{e^{-\lambda} \lambda^{i}}{i!}, \tag{4.1}$$

where *e* is the Euler's constant.

Within the GUI's calculation section, this equation is shown together with its the appropriate results. Moreover, in order to further aid with the teaching and learning of this mathematical phenomenon, the proposed TUI system graphically displays dynamic Poisson distribution graphs for each entity. These are projected directly adjacent to the respective arrival and service tangible objects, as visualised in Figure 5.20(a). Upon rotating the angle of the respective physical objects, students can alter the corresponding rate parameter and consequently, this results in a dynamic alteration of the distribution shape as seen in Figure 5.20(b). Furthermore, in each stochastic instance, the system generates a random number for the interarrival/service delay of the simulated element, which is subsequently conditioned according to the appropriate distribution. To assist students in visualising this process, an animated element represented as a dark '*dot*' is made to move along the graph until it reaches the estimated time, at which point the animation changes the elements' colour and shifts it to the subsequent queue segment area. This allows students to intrinsically apprehend the probabilistic nature of stochastic events and understand the eventual natural distribution of elements following a number of iterations.

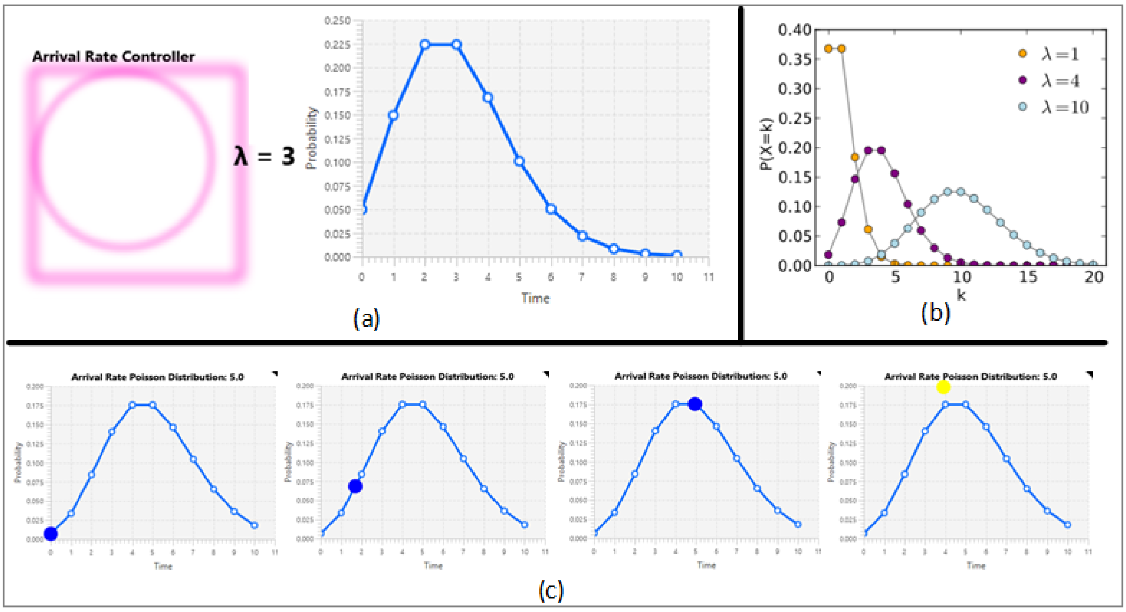


Figure 5.20 Designed TUI interactive elements for statistical representation including;

a) Graphically displayed Poisson distribution curve adjacent to the tangible object

b) Variation of statistical distribution according to the configured rate parameter.

c) Animated sequence of element following a distribution delay.

Assuming an infinite buffer-size (K=∞), animated elements would flow directly into to the service modelling sector of the queue. The layout of this segment is designed in a similar manner to the arrival segment with a TUI placeholder and corresponding Poisson distribution curve in its adjacency. An animation sequence is also undertaken in a similar fashion to the captured images of

Figure 5.20(c), hence allowing students to solidify their understanding of stochastic processes and functionality.

The proposed system initializes the queuing model upon establishing of the first service rate (μ_1) via the placement of a tangible server model. Within this mode, the system commences an *M/M/1/K* queuing model and displays to the users the mathematical calculations for this operation within the equations segment. These include the system utilization factor (ρ), the average amount for elements in the system (N), and the average waiting time elements spend in the system (T) defined respectively as;

$$\rho = \frac{\lambda}{\mu}, \tag{4.2}$$

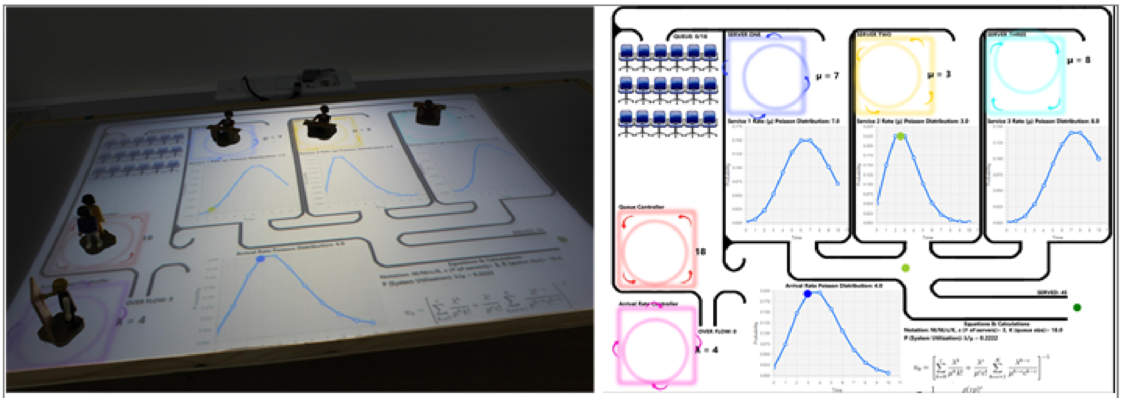
$$N = \sum_{n=0} n(1-\rho)\rho^n = \frac{\rho}{(1-\rho)}, \tag{4.3}$$

$$T = \frac{N}{\lambda} = \frac{1}{(\mu-\lambda)}, \tag{4.4}$$

The runtime computation of these calculations allows students to understand and visualise in real-time the theoretical system parameters whilst understanding the mathematical models defining the queue's operation. The proposed TUI system is then able to automatically shift towards an *M/M/c/K* model once the users introduce the second or third server, whereby the queuing model distributes the buffered elements sequentially to available servers according to their individually configured service rate (μ_c). Consequently, Equation 4.4 is amended in order to account for a multiple-server scenario using the calculation

$$T = \frac{1}{\mu} + \left[\sum_{k=0}^{c} \frac{\lambda^k}{\mu^k k!} + \frac{\lambda^c}{\mu^c c!} \sum_{k=c+1}^{K} \frac{\lambda^{k-c}}{\mu^{k-c} c^{k-c}}\right]^{-1} \left[\frac{\rho(cp)^c}{\lambda(1-\rho)^2 c!}\right], \tag{4.5}$$

The simplicity of physically constructing and configuring the TUI system allows students to appreciate the repercussions of the developed models via simulation, whilst at the same time understand the underlying mathematical foundations as depicted in Figure 5.21(b). This is made possible via the intrinsic interlink between the digital model and the physical realm. As evidenced by the comparative images of Figure 5.21, students are able to manipulate the object-based topology whilst concomitantly visualise the digital functionality and visual algorithmic computations.



(a) (b)

Figure 5.21 Simultaneous configured queuing model within;

a) the physical domain,

b) the digital domain.

The queue/buffer parameter (notation "K") of the simulated model is presented as an optional attribute to the system. Until students explicitly utilize the respective tangible object within the corresponding placeholder area, this parameter is considered as infinity (∞) and the model behaves as an *M/M/1* or *M/M/c* queue. Once quantified the queue/buffer size is set to a finite number and this is visually represented as a seating area within the system as illustrated in Figure 5.22(a). Physically rotating the tangible object increases or decreased the queue size, and this is dynamically reflected on the number of "empty chairs" displayed on the interactive surface. The presented queueing theory is computed on a first-come-first-serve basis and on each completed service, the queued elements are visually moved along the waiting line to highlight the buffer operation to students. The equation section dynamically displays to the user the system's probability of blocking/overflowing a packet and this calculation is further visualised in the equation section as;

$$P_{block} = \frac{(1-\rho)}{(1-\rho^{K+1})}\rho^{K}, \quad (4.6)$$

and updates Equation 4.4 to account for finite buffer capacity:

$$N = \frac{\rho}{(1-\rho)} - \frac{(K+1)}{1-\rho^{K+1}}\rho^{K+1}. \quad (4.7)$$

In instances in which the capacity of the queuing area is reached, newly incoming elements are turned away and these are animated and accumulated within an overflow counter as captured in Figure 5.22(b).

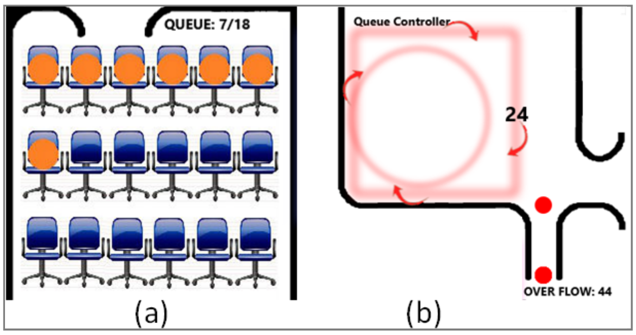


Figure 5.22 Tangible interaction design for queue/buffer parameter through;
a) GUI depiction of configured queue capacity
b) Overflow animation with accumulation counter.

5.4.2 Experimental Results and Discussion

The developed TUI system was deployed for evaluation at Middlesex University Malta within the undergraduate degree in Computer Networks. Queuing theory is harboured as a threshold concept within a second-year module named Networking Design and Simulation and thus the TUI system was strategically implemented to coincide with the delivery of this topic.

5.4.2.1 Evaluation Methodology and Results

Thirteen (13) students who were reading a Computer Networks degree in part-time mode volunteered for evaluation and were subsequently randomly split into two groups of seven (7) and six (6). The latter would serve as a control group for the evaluation whilst the former group would constitute the experimental cohort.

To eliminate any potential bias within the students' prior knowledge and/or experience with this conceptual deployment in the field of computer networks, all students were provided with a timed pre-test consisting of 14 open-ended questions relating explicitly to the technical and conceptual understanding of queuing theory as detailed in Appendix B.3.1. The results served to compile an individualistic baseline for each student through which improvements in gained knowledge would be measured.

Subsequent to this assessment, the volunteering students were split according to their random group assignment and the control group was provided with an introduction to the concepts of queuing theory using a traditional lecture technique involving projected slides and whiteboard usage. The experimental group was separated and placed in a different classroom whereby consecutively they underwent the delivery of the same material using instead the proposed TUI framework as shown in Figure 5.23.

Figure 5.23 Evaluation session of the proposed TUI system for teaching and learning queuing theory concepts.

To ensure coherent conditions, both groups were instructed by the same lecturer and directly following their respective session, each group was provided with a second post-test assessment. The latter was also composed of 14 open-ended questions, which however albeit assessing the same body of knowledge as shown in Appendix B.3.2, were structured differently to avoid possible influence from the previous question set. The assessment scores obtained by each student for pre-test and post-test are presented individually in Figure 5.24.

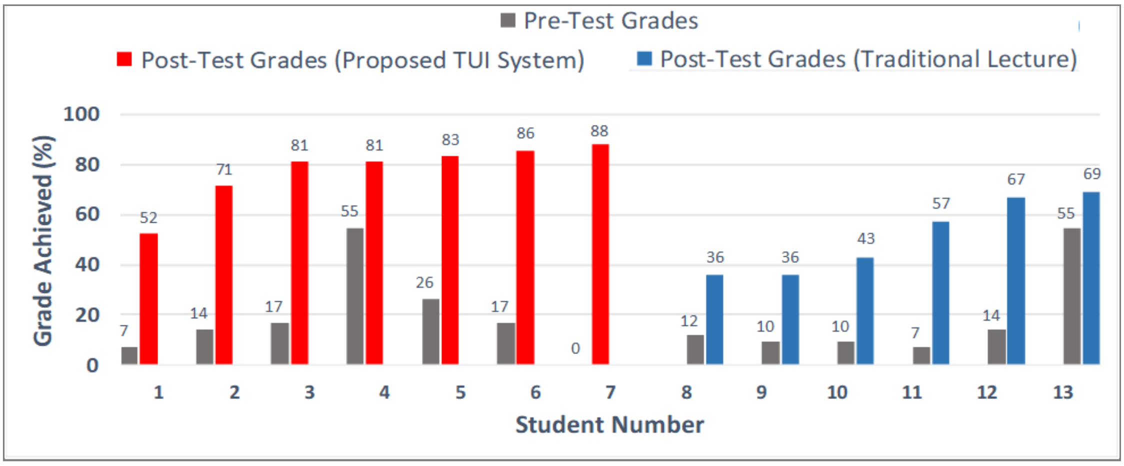


Figure 5.24 Student profile comparison of academic assessments prior and following tuition on queuing theory.

The pre-test grade distributions (grey) within Figure 5.24 highlight that the a priori knowledge on queuing theory by students within both cohorts does not differ significantly ($\rho > 0.8$). This result indicates that no knowledge bias was attributed to the selection strategy and thus the random splitting approach adopted in the evaluation methodology was appropriate.

A paired sample test on the results of the traditional lecture cohort illustrates that following the tuition intervention the control group students increased their assessment grades from 17.8% (σ: 18.2) to 51.2% (σ: 15.0), hence obtaining an average knowledge gain of 33% (SD 15.1%). Whilst successful in providing students with a basic understanding of queuing theory concepts, the achievement of conventional lectures was however drastically outdone in comparison to the success registered by students who utilized the proposed TUI system. A similar paired t-test on the experimental cohort enumerated an assessment grade improvement from 19.4% (σ: 17.6) to 77.5% (σ: 12.3) hence students obtained a knowledge gain of 58% (σ: 19.3) in technical questions directly related to queuing theory fundamentals. This disparity was further stressed by an independent sample test which asserted that the observed difference had a statistical significance of $\rho < 0.01$.

5.4.2.2 Discussion and Feedback Analysis

The quantitative evaluation derived from the assessed variance in academic achievement within students thus serves as an objective appraisal for the proposed TUI design. This directly reflects on the efficacy and aptness of employing a TUI framework for teaching and learning of abstract mathematical concepts such as queueing theory within the pedagogy of engineering.

Furthermore, a subsequent qualitative evaluation was also undertaken on the experimental cohort who made use of the TUI system for instruction. Students were asked five generic questions based on their user experience within the session and their interactivity with the proposed TUI framework. The resultant feedback was aggregated and tabulated in Figure 5.25.

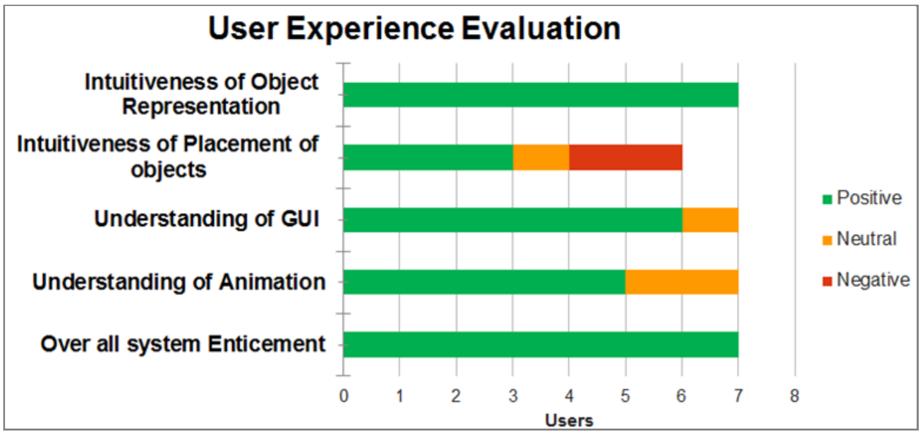


Figure 5.25 Aggregated user experience evaluation following the interaction with the proposed TUI system

The feedback acquired from evaluating students clearly highlights that apart from their academic improvement, which was not communicated at the time, the proposed TUI system was positively received by students and the system served to entice learners to understand the presented queuing theory concept. The case scenarios used via the tangible objects were also positively received and aided students in assimilating the explained concepts with everyday examples. Future work, however, should focus on making the GUI more intuitive especially with respect to associating tangible objects with their designated placeholders. Also, the ability to pause or slow down the simulation process in some instances was highlighted to be beneficial as an improvement feature which would allow easier visualisation and understanding of underlying processes.

5.5 Multi-threaded Task Scheduling

Over the past years, market commoditisation has been shifting technical advancements such as the integration of multiple central processing units (CPU)s from a previously specialised domain associated with supercomputers to proliferation in laptops and mobile systems (Wolffe and Trefftz, 2009). As parallel computing gained increased significance in the industry, this has in turn directly affected the educational curricula (Bi and Beidler, 2007), with students in computer science being compelled to familiarise themselves with the different approaches to managing parallelism in order to have the ability to eventually exploit future computing technologies (Wolffe and Trefftz, 2009).

With multi-thread programming becoming the method of choice in parallel computing (Bedy *et al.*, 1999), the emphasis within the industry is ever-more focused on the “real performance” of systems and hence impelling programmers to consider the overall execution time of their software (Giacaman, 2012). Thus, whilst teaching modern programming languages today, lectures must go beyond object-oriented concepts and promptly introduce students to built-in thread functionality within languages to deal with concurrency and inter-thread synchronisation issues (Bi and Beidler, 2007).

As explained by the Malnati *et al.* (2007), introducing the paradigm of ‘*multi-threading*’ poses significant challenges for both the lecturer; who needs to find the best way to explain the abstract concepts, as well as for students who fail to understand what is happening to their programmes (Malnati, Cuva and Barberis, 2007). This difficulty was practically experienced in the study by Shene (1998) which reiterated previous claims, highlighting the need for changing the students’ thinking paradigm from that adopted in sequential programming (Sutter, 2005).

Further adding complexity to multi-threaded programming is the fact that debugging and analysis techniques which are commonly adopted in single-threaded applications do not provide the same relevant information to reconstruct the parallel execution of programs (Bi and Beidler, 2007).

5.5.1 Educational Technology for Multi-Thread Task Programming

To overcome this limitation and mitigate the loss of students' confidence in understanding what is happening at runtime to their code (Malnati, Cuva and Barberis, 2007), a number of software tools have been developed that log the concurrent execution of instructions on different threads and visually display these using UML and other software development tools (Mehner, 2002; Oechsle and Schmitt, 2002; Leroux, Réquilé-Romanczuk and Mingins, 2003). Whilst these approaches provide a significant aid for students to understand multi-thread runtime execution (Bi and Beidler, 2007; Malnati, Cuva and Barberis, 2007), they intrinsically require successive iterations of code programming and execution to generate useful results. The latter can in fact only be derived in post-execution of different multi-threaded configurations, upon which students can finally comparatively evaluate simulation scenarios (Trümper, Bohnet and Döllner, 2010).

Apart from the overt implementation of PC-based systems, weak research efforts have been done in using TUI as an educational technology to explain programming related concepts. Rodríguez Corral *et al.* (2014) employ a gamified approach to introduce basic concepts for object-oriented programming (OOP). The study employs the use and programming of Sifteo cubes (Merrill, Sun and Kalanithi, 2012), which are autonomous microcontroller-based devices, by students during their course. Whilst results illustrate that this technique augmented the interest levels and consequently the achieved marks by students (Rodríguez Corral *et al.*, 2014), the technique does not focus on the tangible aspect of teaching and uses Sifteo cubes mainly as a code execution platform rather than the Integrated Development Environment (IDE) on a conventional computer. Another study aimed to introduce aspects of programming recursion in the Erlang functional language by linking a TUI system in conjunction with Augmented Reality (AR) was done by Vidarte *et al.* (Vidarte *et al.*, 2010). Whilst succeeding to visualise programming stacks in single-tailed-recursive structural functions, the technological interactions of the system are not widely applicable (Vidarte *et al.*, 2010) and the system makes use of tangible blocks merely as optical markers for controlling pure AR virtualisation.

5.5.2 Task Scheduling TUI Framework

In light of the above constraints and the limited adoption of computer-based technology within literature for explaining the concepts of concurrency and inter-thread synchronisation, this section proposes the adoption of a TUI framework to provide students with the ability to interactively comprehend the abstract nature of multi-threaded execution. The unique contribution of this framework lies at the confluence of research streams in the literature on TUI implementations and multi-threading education. Thus, the proposed TUI framework will be discussed and evaluated for its efficacy and aptness in aiding the teaching and learning of abstract and complex concepts such as those present within the task scheduling of a multi-threaded environment.

5.5.2.1 Tangible Interaction Design

The proposed framework was designed to challenge students in allocating a number of computationally complex operations for execution on multiple threads using a TUI approach. Thus, in line with the TUI tabletop architectural design described in chapter 4, the proposed framework engaged students interactively through a tangible set of 3D physical objects. These manipulatives provide direct control over the configuration and setup of multi-threaded scenarios, thus enabling a constructivist design of evermore complex conceptual environments. To aid cognitive embodiment of system interaction, the physical design of the tangible objects was thus designed so that representational models inherently symbolise and express the different computationally complex procedures which would undergo multi-threaded execution within the system. A selection of four commonly used processes in the field of computer-based processing were identified by these criteria including; *downloading content from the internet*, *compressing files*, *image processing* and *content searching*. The representation of these computational processes, as shown in Figure 5.26, were hence designed so as to ensure an innate familiarity and instinctive recollection of the logical and computational tasks associated with these entities.

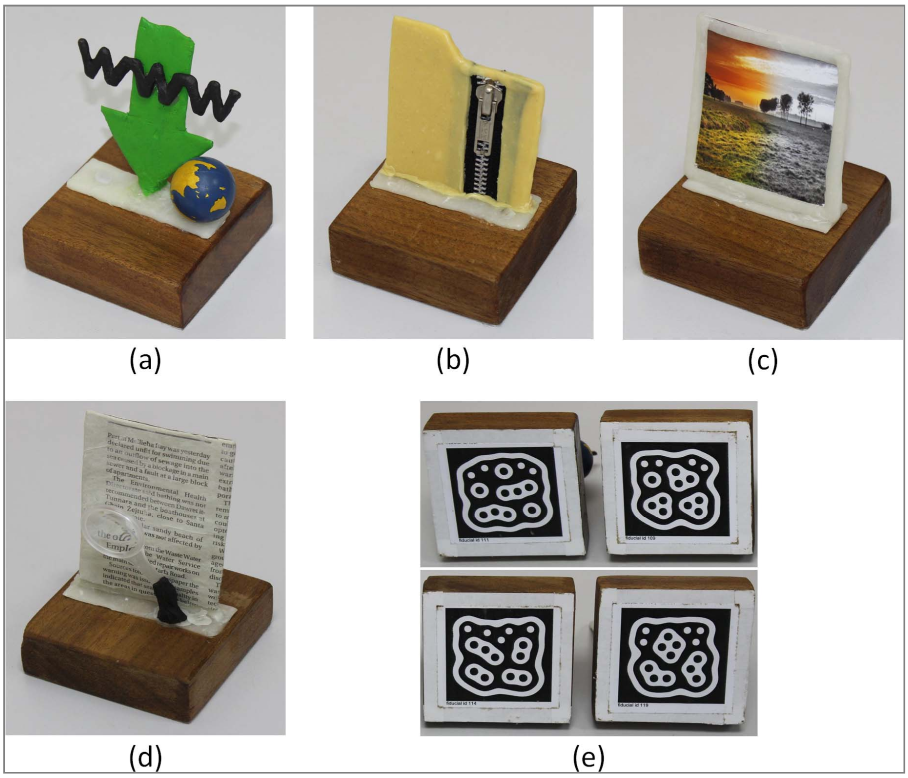


Figure 5.26 Design of tangible objects representing distinct processes;
a) downloading internet content, b) file compression, c) image processing,
d) content searching, e) reacTIVision 'amoeba' fiducials (Bencina and Kaltenbrunner, 2005).

The following descriptions thus highlight the design element considerations within the individual feature representations visualised in Figure 5.26;

- Internet Downloads - Figure 5.26(a): A green downward facing arrow was implemented, typical of internet browser icons for this process, together with the symbols 'www' and a globe both common representatives of the internet.

- File Compression - Figure 5.26(b): A yellow folder shape was used onto which a physical runner was integrated to represent the widely employed file archiving technique using the 'zip' compression algorithm.
- Image Processing - Figure 5.26(c): One of the basic and most commonly the foremost operation on image processing algorithms entails grey scaling of the digital image. This was represented using a photo with two colour variants (full colour and greyscale) within a typical photo frame.
- Content Searching - Figure 5.26(d): A newspaper article is represented in miniature with a magnifying glass physically oriented on parts of the text to represent the commonly employed symbols for computer text searching.

Each object was mounted onto an 8cm x 8cm wooden platform which was designed so as to allow comfortable physical control and interaction with the objects. The size of this wooden platform also enabled the scaling of reacTIVision 'amoeba' fiducials (Bencina and Kaltenbrunner, 2005) to be attached underneath as seen in Figure 5.26(e). These symbols are orthogonally optimized for unique identification of each object, its centre point as well as the rotation angle of the tangible device using the installed camera.

As detailed in chapter 4, the designed architectural setup provides users with the ability to interact in real-time with the system through accurate fiducial positioning, whereby placement of the objects in specific areas on the table triggers different algorithms. A timer was employed for this purpose which locked-in a tangible entity within the computational framework once the former is placed statically in a location for more than five seconds. The proposed framework also makes intrinsic use of positional shifts of tangible objects as an interaction domain. Once locked within a process, the TUI objects are consistently spatially tracked and the system reacts according to the direction of motion followed. The unique nature of the 'amoeba' fiducial symbols further provide rotational uniqueness, which the TUI framework exploits to provide an additional domain of interaction whereby students can alter the attributes of a process by rotating the physical object in a clockwise or anti-clockwise direction.

5.5.2.2 User Interface Design

Inherent to the benefits conveyed by proposed TUI system is the ability to enhance and interweave the physical tangible objects with digital information. Perceptual coupling of the interactive embodiment is achieved by projecting onto the table a dynamic GUI which receives and reacts to controls and inputs provided from the tangible devices. Information, colours and sounds are dynamically altered as students interact with the platform and these provide direct feedback and computational coupling to the interactions undertaken by the tangible objects. Interfacing with the developed Java-based software algorithms, the GUI was developed using the JavaFX library, which enabled the use of visual components such as gauges and dynamic charts to further explain the occurring processes.

In line with collaborative learning design, the GUI developed within the TUI framework, as illustrated in Figure 5.27, consisted of four main spatially distributed areas; the status dashboard, the queue and CPU loading dashboard, the processes description listing, and the thread and tasks area.

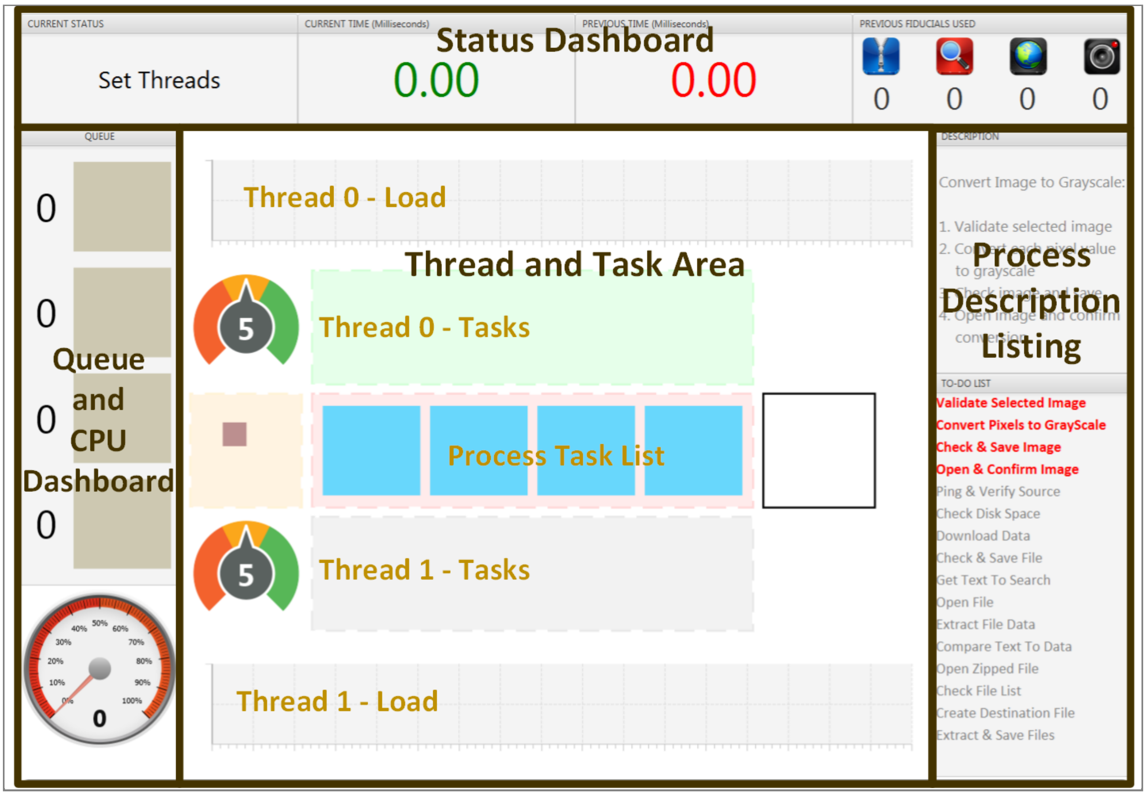


Figure 5.27 GUI design layout segmented according to the four main interactive areas [4].

The top segment of the GUI, depicted in Figure 5.28, provides the student with both information about the current state as well as data from previous system configurations, which can be used for real-time comparison. This dashboard affords students the ability to undertake a direct comparison of both the current and previous simulation execution timings (in milliseconds) respectively. Furthermore, the user can also keep track of the number of processes executed in the previous run by means of representative icons on the top-right corner which provide a contextually detailed comparison of the tasks undertaken. The Queue and CPU dashboard compliment this data by providing further information about the current simulation setup and enlisting process tasks which are queued for execution. Moreover, as seen in Figure 5.29(b), an interactive gauge was designed which measured the real-life CPU load during runtime across both threads. The queue illustrated in Figure 5.29(a) was designed to

[4] Video clips of Multi-Threaded Scheduling TUI framework available on https://youtu.be/dAjK9-ijLM8

serve also as placeholders for the tangible objects being used so as the current processes queued can be visually associated using respective TUI objects.

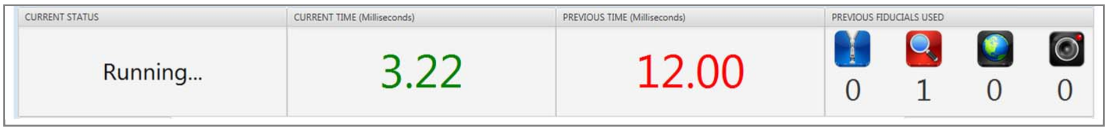


Figure 5.28 Status dashboard highlighting current system execution timings and state in direct comparison with previous process execution.

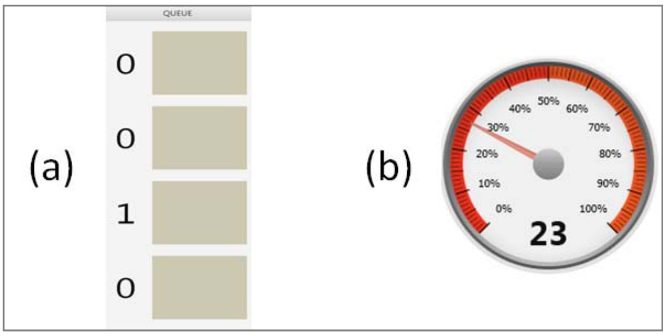


Figure 5.29 Queue list for current simulation setup, together with CPU load monitoring gauge during multi-threaded execution.

The right section of the GUI interface was designed to contain a process description of the locked-in object, as well as a breakdown of the selected process into distinct task lists which need to be dependently executed as depicted in Figure 5.30(a). These are highlighted upon process selection and a red/green colour schema, captured in Figure 5.30(b), is used to discriminate tasks which have been allocated on threads and others that still need to be scheduled. Moreover, this task list is also used during the configured simulation of multi-threaded execution to highlight the tasks which are currently being considered and locked-in by the system. As shown in Figure 5.30(c), the description section serves also as an area to explain to the students any execution error or exception encountered and thus provides formative feedback on the system status accordingly.

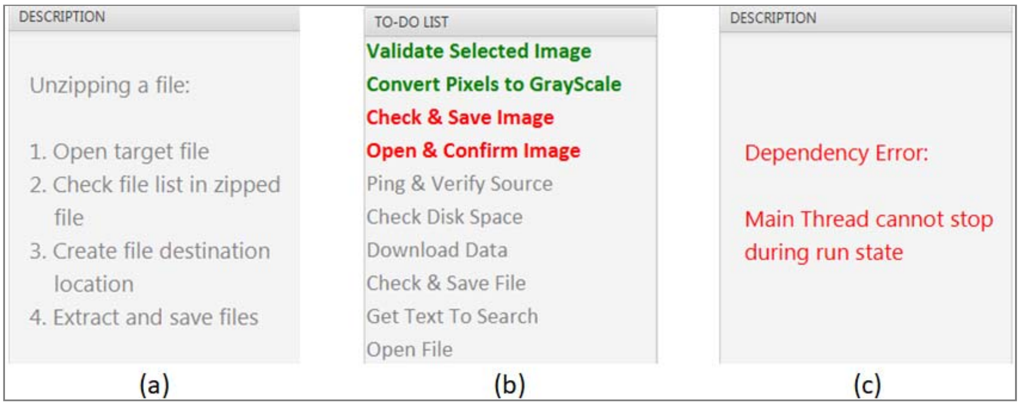


Figure 5.30 Process description list with task list breakdown used for scheduling and status feedback.

The central area within the system interface, highlighted in Figure 5.31, provides an interactive tangible design for enabling process task allocation. To aid explaining multi-threaded scheduling concepts, the system adopted a two-threaded design which allowed for a reduction in numerical complexity as well as aided better visualisation by students. Thus, this section is chiefly composed of the main and secondary threads, denoted as Thread 0 and Thread 1 in Figure 5.27. Furthermore, a process breakdown section in the centre was designed whereby locked-in processes are decomposed into sub-tasks and these are assigned onto individual threads through positional shift manipulations on the respective tangible objects. The thread load area further allows the student to dynamically identify the sub-tasks that have been assigned to each thread, as depicted in Figure 5.31, with each process allocated a unique colour in harmonisation with the tangible object. The interface conveyed the concept of time by spreading task duration along the horizontal axis in line with conventional task process depiction on operating systems.

Figure 5.31 Interactive design for thread visualisation and process task allocation.

5.5.2.3 Interactive Session

A complete session of the system is best understood as a series of constructivist stages within which the students undertake the setup of evermore complex multi-threaded environments. Making use of the TUI objects photographed in Figure 5.26, students are able to add a number of processes onto a thread queue which is then compiled and run with the execution time highlighted in the dashboard of Figure 5.28. As illustrated in Figure 5.31, once a tangible object is placed onto the process placeholder area, a lock-in five-second countdown timer is commenced after which the individual process is decomposed into a set of sub-tasks placed in the middle of the process area as visualised with the blue components in Figure 5.27. The description and to-do list sections, illustrated in Figure 5.30, are concurrently updated and visualised accordingly.

Making use of the same tangible objects, students are subsequently able to allocate individual sub-process tasks onto either the main or secondary thread by physically dragging each task accordingly. In order to aid the understanding of task concurrency decisions, once locked-in on a sub-process, adjacent information is projected about the individualistic task duration and its relational dependency as seen in Figure 5.32(a). Upon placing each sub-process into the thread task area, three circles highlighted in Figure 5.32(b) are displayed and the students can alter the task priorities by rotating and angling the tangible object to the selected value. This decision, in turn, affects the whole thread priority which will be assigned the highest allocated value as seen in the thread gauge Figure 5.32(b).

Figure 5.32 Visualisation options for information relating to task dependency and user-allocated priority.

Following the successful allocation of the sub-tasks within a process, students can either opt to assign additional processes to the threads as illustrated in Figure 5.31 or allow a dedicated countdown timer of ten seconds to elapse following which simulation of the assigned tasks will commence. At runtime, the system will start completing the processes accordingly whilst updating the CPU gauge and the current time display in the status dashboard. Progress is tracked by students using the highlighting of the tasks being executed inside the to-do-list panel. Finally, a session ends with the execution duration and process details displayed to students in the status dashboard as shown in Figure 5.28, whereby details are also kept of previous runs for direct comparison of multi-threaded process allocation setups.

The system also detects exceptional instances when the main thread has been incorrectly allocated and scheduled to be idle whilst processes would still be running on the secondary thread. To allow students to visualise and understand the execution process undertaken in such an instance, the TUI system pauses the execution timer and an animation is displayed whereby progressive transfer occurs of the currently executing task from the secondary thread towards the main thread, after which the system execution carries on normally. Alternatively, if the student incorrectly allocated tasks which conflict at execution time due to internal process dependencies, an error notification is displayed by the system and execution is halted while details are displayed in the description area as shown in Figure 5.30(c). In both these exceptional instances, the user attention is further engaged by the TUI system through the use of appropriate sounds and animations. These instances provide direct formative feedback of underlying conceptual aspects and hence aid the student's cognitive learning process.

5.5.3 Experimental Results and Discussion

The implementation of the TUI framework was undertaken at Middlesex University Malta within a degree programme of computer science. second-year students reading a module in "Engineering Software Development" were selected for summative evaluation. These candidates had prerequisite knowledge in object-oriented programming basics and were introduced during their second year of study to concepts of computer architecture and operating systems. The topic of multi-threaded task scheduling presents a threshold concept within the syllabus of this module and the evaluation session was coordinated to coincide with the formal introduction to the multi-thread programming concepts.

5.5.3.1 Evaluation Methodology

A group of 19 students aged between 17 and 26 years old were recruited based on a purposive sampling technique. A random selection of seven (7) students were selected for the experimental group whilst the remaining twelve (12) students composed the control group for the evaluation study. The selection of less students for the experimental group was based on the physical constraint on the number of students that are able to successfully huddle around whilst comfortably interact and participate with the tabletop architecture. The control group was subjected to a traditional lecture for introducing multi-thread task scheduling, whilst the experimental group made use of the proposed TUI system for an explanation of the same multi-threaded concepts. In order to reduce variable conditions between both cohorts, each session was allocated a fixed time and delivered by same module lecturer sequentially on the same day.

The module was studied by students reading their degree in either full-time or part-time mode. This introduced a potential variation between students owing to their individualistic exposure and practical experience towards the subject of multi-threaded software development from potential industrial and development experiences. Whilst the theoretical concepts of multi-thread task scheduling would be introduced within the coordinated session, an a priori examination was undertaken by all students, so as to establish an a priori individualistic knowledge baseline. This assessment was composed of ten (10) multi-thread scheduling related questions posed as a combination of open-ended and multiple-choice questions as attached in Appendix B.4.

Following this test, grouped students were split into different rooms, for undertaking their respective introduction session to multi-thread task programming. Whilst the control group used conventional technological equipment such as video projection and smartboard setups within a traditional lecture, the TUI session complemented the same projected slide material with an interactive explanation undertaken on the proposed framework. Both sessions covered identical technical content and task examples, which involved mainly the understanding of various multi-threaded scheduling concepts and their potential related errors. Further to completing the tuition session, each cohort was provided with a second assessment questionnaire. This test, whilst containing different questions than the first one, covered similar multi-threaded conceptual knowledge, once more using a combination of open-ended and multiple-choice questions.

The evaluation process was hence designed to yield a quantitative analysis, whereby students would be evaluated on their answers to academic achievement and conceptualised knowledge. This provided the necessary data to objectively compare and quantify the ability of the proposed teaching methodology to convey the abstract notions of multi-threaded task scheduling procedures.

5.5.3.2 Results and Discussion

The data in Figure 5.33 represents the results obtained from all the participating students within their common pre-test technical questionnaire. The average mark obtained by the entire class in this initial test was of 27% with a standard deviation (σ) of 12%. The normally distributed data for this initial test, moreover confirms that all students had a generally similar a priori understanding of the conceptual multi-threading aspects.

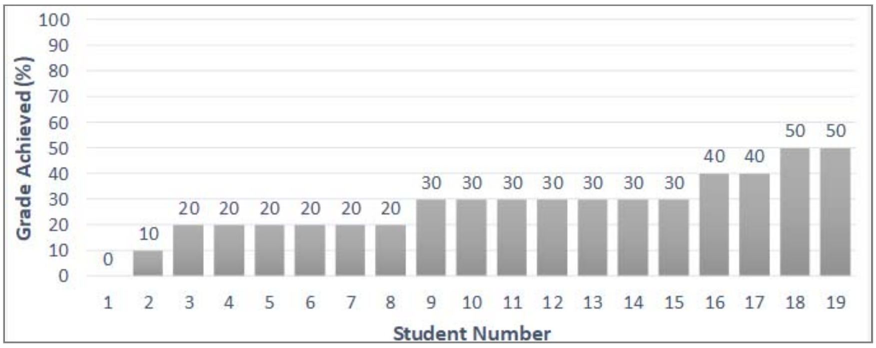


Figure 5.33 Individual student grades during an a priori examination.

As detailed in the evaluation methodology, following each teaching intervention, a second technically similar test was provided to students. This allowed for a direct relational deduction of each student's individual ability to understand the multi-threaded concepts conveyed in the respective session. The results in Figure 5.34 illustrate a personal comparison between the before and after grades obtained by individual students attending a traditional lecture on multi-threaded task scheduling (Figure 5.34(a) - blue) with respect to the experimental group using the proposed TUI system (Figure 5.34(b) - red).

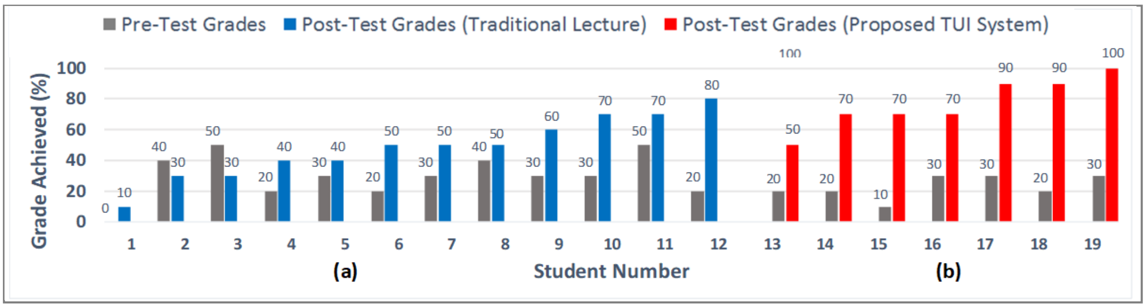


Figure 5.34 Individualistic student comparison between test grades obtained before and after attending a learning session using; a) Traditional lecture session, b) Proposed TUI system session.

The comparative histograms in Figure 5.34(a) highlight that following the attendance to traditional lecture, in general students improved their understanding of multi-threaded programming, with an average assessment progress from 30% (σ: 14.1) to an average mark of 48.3% (σ: 19.9). Moreover, the exceptional instances of participants 10 and 12, the evaluation highlighted instances of students who failed to understand the provided content and thus weren't able to answer the second set of questions correctly with their obtained knowledge. Nevertheless, a paired sample t-test on the marks obtained by each student in this lecture-based group showed that an average grade increase of 18.3% (σ: 20.3) has been registered with $\rho < 0.05$ and a test statistic of 2.99.

In relation to the control group, the students who learnt multi-thread concepts whilst using the proposed TUI system, Figure 5.34(b), demonstrated an average mark increase from 22.8% (σ: 7.6) to 77.1% (σ: 17.0). A separate paired sample t-test on the a priori and a posteriori grades obtained by the experimental TUI learning cohort proved that the average grade increase of 54.3% (σ: 13.9) was statistically significant at $\rho < 0.001$ and a test statistic of 9.50. The mean difference in the grade improvement of both teaching techniques is depicted in Figure 5.35 together with the respective 95% confidence lower and upper bounds.

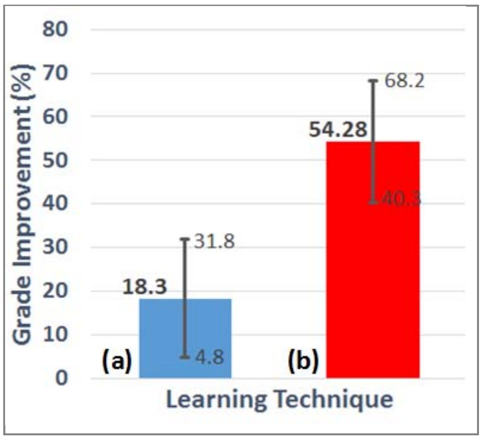


Figure 5.35 Relative grade improvement obtained by students at 95% confidence bounds in a posteriori examinations following; a) Traditional lecture session, b) Proposed TUI system session.

An independent sample t-test was further undertaken on the relative grade improvement from both examination marks between the two groups. Albeit, some variation can undoubtedly be attributed to the smaller group size tested for the TUI experiment, the results categorically endorsed the fact that students learning the abstract concepts of multi-threaded task scheduling using the proposed TUI system were able to attain 22.8% (σ: 9.0) higher grades than the control group. This discrepancy was stated under Levene's test for equal population variance which proved the result statistically significant at $\rho < 0.005$. The positive results from utilising the TUI system were also resounded subjectively by the students and lecturer alike, which reported a heightened sense of engagement and attention whilst interacting with the proposed system. This encouraging phenomenon was observed both in terms of increased participation in discussions during the topic explanation as well as augmented group collaboration between students whilst configuring the system.

5.6 Search-Space Problems

The proliferation of artificial intelligence (AI) has progressively evolved the domain from a specialization in computer science to nowadays most aspects of software and systems engineering (Agrawal, Gans and Goldfarb, 2017). This advancement has naturally led HEIs to introduce and teach the foundational concepts of AI within an ever-growing portfolio of undergraduate and graduate programmes (Wollowski *et al.*, 2016).

Nevertheless, the teaching and learning of fundamental AI concepts such as: search, knowledge representation, and machine learning prove a challenge to deliver and understand within undergraduate courses for both lecturers (Parsons, 2004) and students alike (Friese and Rother, 2013). This claim has been supported by various educational research, outlining difficulties in both explaining the abstract conceptual content involved (Kumar and Meeden, 1998; Gulatee and Combes, 2006), and those experienced by students in visualising these notions (DeNero and Klein, 2010). These inherent difficulties further hinder students in applying and understanding AI theory from both conceptual viewpoints as well as from the required practical and technical perspectives (Friese and Rother, 2013).

5.6.1 Teaching and Learning Search-Spaces

Furthering the complexity of introducing AI within education is the breadth of topics that are entailed within the field, which often leads to overwhelming students with an incoherent set of disjoint topics (Freeman and Silverman, 1993). This phenomenon is commonly referred to as the 'Smörgåsbord' problem (Soliman and Elgendi, 2014). To aid correlate these domains together, the foundational concept of state-space-search (a.k.a. 'search-spaces') has commonly been utilized as a unifying theme for AI topics (Thornton and du Boulay, 1992), providing a constructive platform onto which students can amalgamate AI understanding (DeNero and Klein, 2010). The vital concepts of search-spaces are nontrivial to explain and understand and often lead themselves to a threshold concept within introductory AI courses (Rountree and Rountree, 2009; Grivokostopoulou and Hatzilygeroudis, 2013).

Unfortunately, the technical and psychological dimensions which students need to mentally map these abstract concepts presents a challenge for comprehension (Friese and Rother, 2013). Students thus struggle to visualise the high-dimension reasoning required whilst at the same time be able to technically implement these abstract algorithms (Meyer and Land, 2003; Male, Guzzomi and Baillie, 2012; Male, Macnish and Baillie, 2012; Janota, ŠimÁk and Hrbček, 2014). The limited capabilities of traditional teaching pedagogies involving tutor-based instruction (Grivokostopoulou and Hatzilygeroudis, 2013) and traditional visual media (Catala *et al.*, 2011), further constrain students' ability to comprehend searching algorithms, consequently reducing the effectiveness of AI lectures (Naser, 2008). This inadequacy led to the development of educational tools which aim to help students in learning and understanding these abstract themes (McSporran and King, 2005).

Using GUI-based software, educational technologies were consequently developed to explain search algorithms via visualisation tools (Barker and Phil, 2008; Naser, 2008). Additionally, the engagement of edutainment alternatives which adopt games to teach AI concepts has increasingly gained popularity with HEIs (Hingston, Combes and Masek, 2006; Hartness, 2009; Wong, Zink and Koenig, 2010; McGovern, Tidwell and Rushing, 2011). The use of gamified educational software for search-spaces is further favored for its ability to exemplify conceptual understanding using classic puzzles such as; *tic tac toe*, *missionaries and cannibals* and *the eight-queen problem* (Levitin and Papalaskari, 2002; Zyda and Koenig, 2008; Uke and Thool, 2011). Moreover, the gamified approach to such transport puzzles exposes students to real-life logistical contexts, which aid to exemplify conceptual processes such as 'path-planning' and 'search methods' whilst increasing students' engagement and learning motivation (Ribeiro, Simoes and Ferreira, 2009).

Regrettably, the focus of games on their inbuilt animated graphics and the enjoyable user experience during puzzle solving often limits the educational elements presented to users to visualise and understand the underlying concepts (Friese and Rother, 2013; Singh and Riedel, 2016). Thus, this leads to the conceptualisation of AI search-spaces to be still widely regarded as a difficult threshold to teach and learn (Russell and Markov, 2009; Janota, ŠimÁk and Hrbček, 2014; Bockholt and Anna, 2015). Moreover, the limited and generic interaction capabilities of GUI frameworks using conventional personal computer setups fail to provide users with an immersive educational experience (Grundy and Hosking, 2000; Freeman *et al.*, 2014). This hinders the students' ability to undertake creative and collaborative learning interactions, thus impeding the effectiveness of learning pedagogies adopted in HEI lectures (Amershi *et al.*, 2005; Blasco-Arcas *et al.*, 2013).

5.6.2 Tangible Approach to Search-Spaces

To this end, this section presents an alternative approach to introduce undergraduate students to AI search-space concepts using an engaging and interactive tangible approach. To contextualize the search-space problem concepts, whilst embedding the gamification benefits within the proposed tangible approach, a variety of educational puzzles were investigated as outlined in the literature (Levitin and Papalaskari, 2002; Zyda and Koenig, 2008; Uke and Thool, 2011). Whilst the familiarity of students with transport puzzles is an asset which is often exploited in educational games, popular versions of these puzzles; such as *Towers of Hanoi* and *Missionaries and Cannibals*, were not deemed appropriate due to their inherent well-known solutions (Bodin and Ershov, 2013). Furthermore, the limited complexity of these puzzle instances fail to provide an engaging problem-solving difficulty to HEI mature students, thus hindering their appreciation of underlying concepts (Kotovsky and Simon, 1990). To this end, a less popular transport puzzle was selected from the 'river-crossing' genre, which is exemplified in the *Japanese family river-crossing* puzzle scenario (JapaneseIQTest, 2015). This example provided a suitable level of problem difficulty due to its exponential search-space size growth as the problem increases in length and complexity, together with a set of non-trivial problem constraints (Knowles and Delaney, 2005). This ensured that students would be exposed to an educational knowledge challenge further to an enjoyable game puzzle.

5.6.2.1 Tangible Interaction

The interactive engagement of students with the proposed approach was achieved via the manipulation of dedicated 3D objects. These physical components, shown in Figure 5.36, were composed of aptly selected figurine models which through a priori student familiarity and association enabled the intrinsic embodiment of various attributes qualities. The design of these objects also took into consideration the size and weight of manipulatives to ensure a comfortable and ergonomic interaction. Thus, each object was placed on a 5cm x 5cm acrylic plastic base, which was coloured on top whilst affixed with a reacTIVision fiducial marker underneath (Bencina and Kaltenbrunner, 2005).

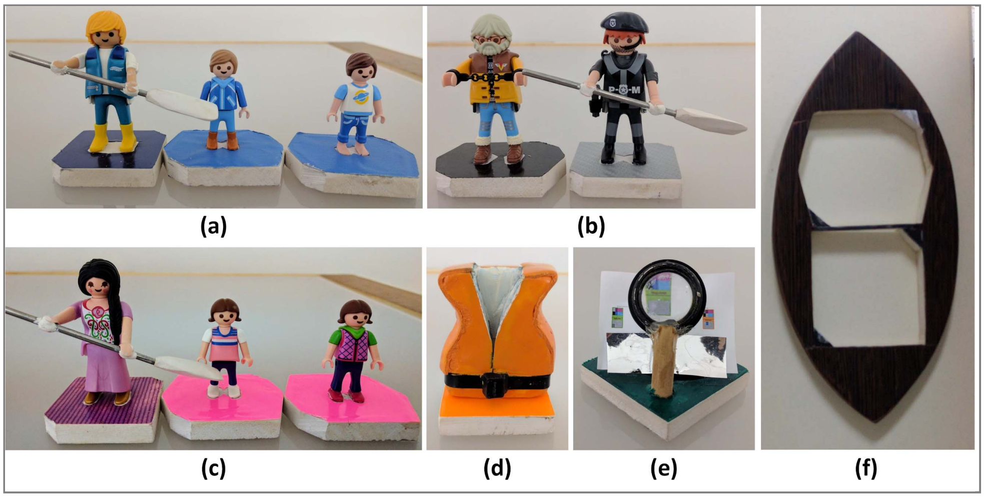


Figure 5.36 Tangible manipulatives adopted during the river-crossing context:

a-c) Figurines representing the exemplified puzzle characters,

d) Hint request tangible shaped as a life-jacket,

e) Search-space manipulative shaped as a magnifying glass,

f) Bidirectional river-crossing raft with passenger/driver configuration.

Various design considerations were undertaken to aid the conceptualization aspects of the developed scenario as well as promote engagement with the proposed TUI approach. These are systematically detailed below:

- Characters – Figure 5.36(a)-(c): These figurines were designed to intrinsically relate to the specific characters in the puzzle scenario providing an intuitive association to the user. A carefully designed color-scheme was adopted on these objects which visually reinforced algorithmic puzzle constraints by ingraining an association between groups of linked characters. To reflect another constraint on the allowed traveling permutations of characters, potential raft *drivers* were equipped with an oar to facilitate the distinction and tangible selection by students.
- River-crossing raft – Figure 5.36(f): This pivotal tangible was designed in line with the 'token-and-constraint' tangible principles (Ullmer, Ishii and Jacob, 2005), whereby a mechanical restraint was adopted to aid students in navigating through the potential search-space. As illustrated in Figure 5.36(f), the restriction was designed to enforce the algorithmic rule of ensuring at least one *driver* character is present in each valid transit combination. To this end, symmetrical mechanical designs were developed on respective figurines to aid students in intuitively identifying roles without distracting concentration from the search-space navigation and conceptualization. Moreover, to prompt the user towards rotational interaction with the tangible, the raft was designed in a circular shape with pointed edges which served as physical dial-pointers to select digital information.
- Tangible Controllers – Figure 5.36(d)-(e): These input manipulatives enabled students to interact in a more engaging manner with the proposed TUI setup. The use of iconic models such as a life-jacket tangible was designed to allow students to seek assistance on valid search-space combinations if students remain stuck in a state for a duration significantly longer than the commonly observed interaction

frequency. This parameter was heuristically optimised during alpha testing to a delay of twelve (12) seconds of inactivity. The magnifying glass object, on the other hand, allowed students to tangibly navigate through the explored search-space and revert to previous states by appropriately undertaking physical positional manipulation and selection.

5.6.2.2 Graphical Interaction

The interlacing and embodiment of digital augmentation on these physical models is primarily obtained via the perceptual and computational coupling of visual information projected onto the tabletop interactive surface. Thus, a graphical user interface was specifically developed for this TUI approach which by vertically splitting the interactive surface as pictured in Figure 5.37, displayed the river-crossing scenario together with visualisation of the explored search-space. As illustrated in captured instance of Figure 5.37(b), upon detection of each tangible, the developed TUI approach provided visual feedback to students by projecting a color-coded square around each tangible, digitally interlinking the objects with the interface.

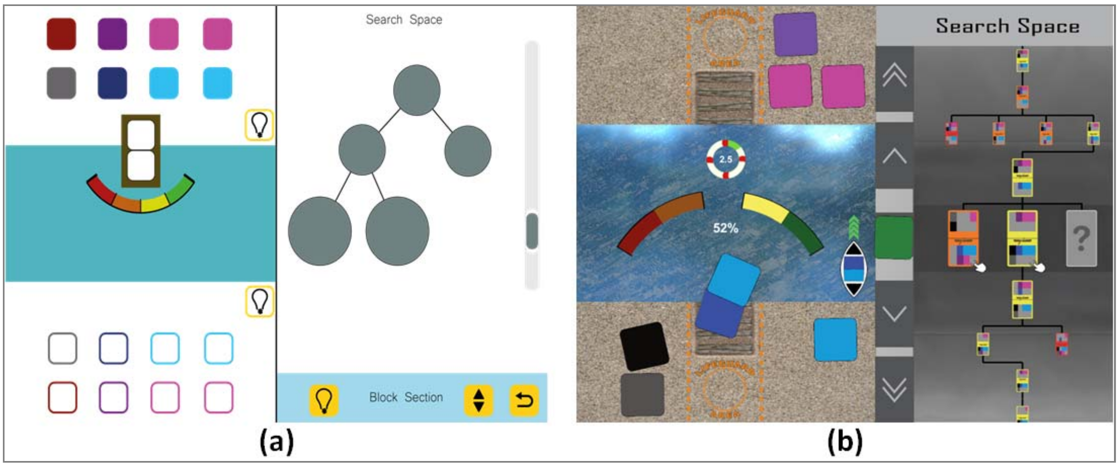


Figure 5.37 Graphical user interface design for integrating a river-crossing puzzle with search space visualisation [5]. Cross comparision between a) GUI Wireframe design, b) Final graphical interface.

[5] Video clips of Normalisation TUI framework available on https://youtu.be/7zlEqO4YtZw

Throughout the execution of search-space exploration via the river-crossing puzzle, the proposed tangible approach integrated numerous visual animations to aid students in progressing through their solutions. These graphical representations were carefully designed to provide intuitive formative feedback to students which instinctively led students to further engage in an active experimental learning pedagogy.

As illustrated in Figure 5.38, a variety of digital imagery and animations are timely projected to provide students indications on the validity of their actions in light of the puzzle constraints. Once a valid placement of characters inside the raft is chosen by students, the TUI framework provides indicative feedback by animating a path to traverse the riverbanks as shown in Figure 5.38(a). On the other hand, if the students select a combination which results in a rule violation, appropriate animations are displayed indicating the nature of the violated rule whilst changing the river colour to red to highlight the error, as visualised in Figure 5.38(b). Moreover, indications are subsequently provided to users to return to the a priori valid state by flashing the respective characters to be added/removed as accordingly shown in Figure 5.38(c)-(d). This interactive feedback is perceptually coupled in the proximity of respective tangibles which provides an augmented understanding of the collaborative actions and decisions performed. Furthermore, this capability allows the TUI framework to introduce students to the concepts of search-space backtracking.

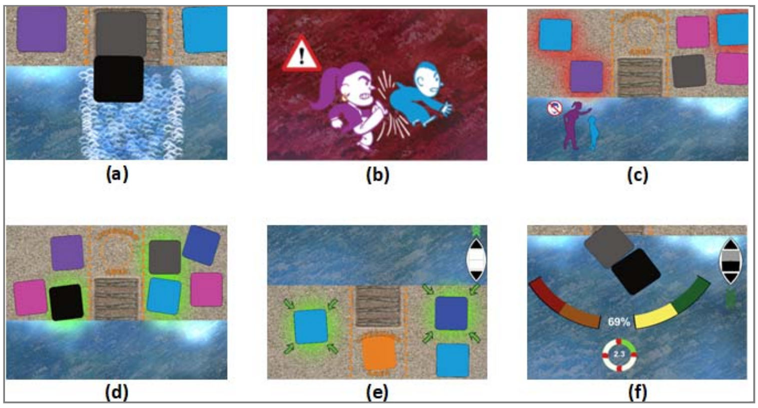


Figure 5.38 Animation images employed to aid students in search space exploration

In providing a hint functionality option when users are stuck within a state for longer than twelve (12) seconds, an orange lifeguard symbol is faded on the interface. This delay was designed so as to avoid the overuse of hints from students whilst at the same time retaining engagement with the system during difficult search-space progression states. Following the engagement of students with this optional functionality via the apposite 'life-jacket' tangible, the algorithmic framework permutes the possible combination options to determine whether options are available. If unexplored possibilities are still present in the search-space, a possible combination is indicated to users using a combination of coloured flashes and highlighting arrows as illustrated in Figure 5.38(e). In order to encourage comprehensive exploration of the search-space, the TUI framework randomises the shown hint option, thus prompting users to consider both valid and potentially invalid states.

Interlaced with the challenging gamified aspect of the puzzle, the tangible approach integrates the educational aspects of search-space conceptualization by multiplexing the tangible and digital interactions. Once students undertake a particular state change selection by physically placing characters within the raft, a confidence dial is digitally projected adjacent to the docked raft as shown in Figure 5.38(f). This circular digital dial prompts users to rotate the raft by physical pointing the tangible towards the selected coloured range. This manipulation presents the proposed TUI approach the ability to allow students to collaboratively determine their confidence-value considered search-state which is recorded by the system. This interaction instinctively prompts students in collaborative interaction and discussion of the search-space validity and understanding.

Moreover, following the consideration of a search-state, the TUI framework populates the left section of the interactive surface, illustrated in Figure 5.37, with a graphical visualisation of the explored search-space. Using color-coded depictions in relation to the confidence-value chosen, the TUI framework coherently interlinks the character state information using associatively coloured icons. Each state is appropriately displayed in the ply of the explored search-space solution and can be navigated through a scrolling approach via the magnifier tangible.

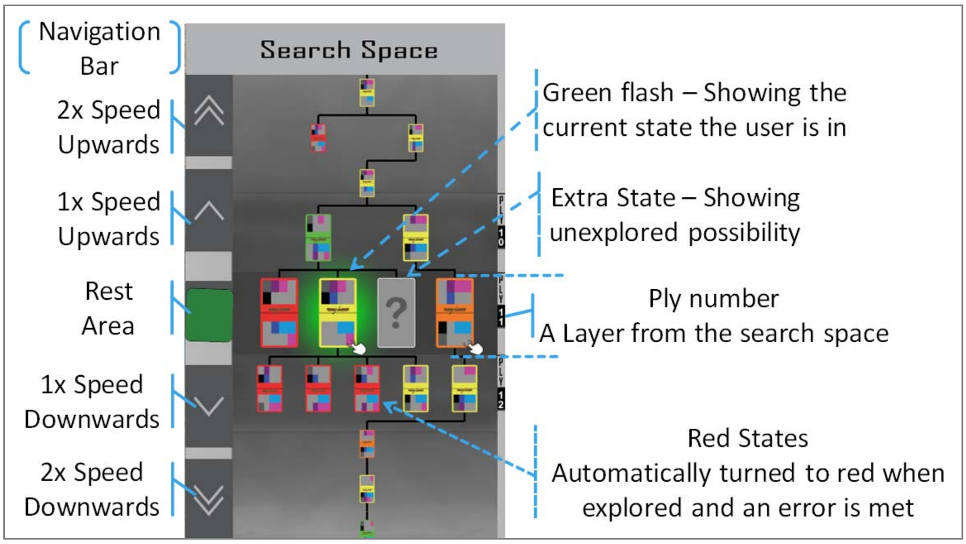


Figure 5.39 Description of search-space interactive area and animations

As shown in Figure 5.39, tangibly navigating through the selection of vertical navigational buttons allows students to zoom into previously explored plies whilst retaining an understanding of the entire search space. This provides learners with the ability to further concretize their understanding of the explored search-space whilst also providing the ability to implement search-space concepts such as backtracking. This functionality is tangibly implemented by providing students with the ability to physically select a previously transitioned state using the magnifying tangible. Digitally, the system would revert to the selected state and indicate to students the tangibles changes needed using graphical cues shown in Figure 5.38(e). Furthermore, in the instances whereby students perform an invalid state action, the TUI framework automatically reflects the violation result of the explored state by altering the assigned state-colour to red indicating no confidence in the potential validly of the state. The developed tangible approach thus enabled HEI students to interactively explore a complex search-space problem using embodied interaction to ultimately converge on the puzzle's solution.

5.6.3 Evaluation Methodology

The experimental evaluation methodology was designed to provide a quantitative analysis of the effectiveness and suitability of the proposed tangible approach to aid conceptual understanding of search-spaces in higher education. More specifically, the intended design aimed to objectively compare the students' knowledge gain following an experimental session using the described tangible approach against that obtained using current search-space GUI-based educational software. This was measured using both open-ended examinations on theoretical and practical concepts of search-spaces as well as a student interaction log which programmatically monitored and assessed the students' exploration of search-spaces whilst solving a problem-based context. To this end, the sequential flow of the evaluation methodology is outlined in Figure 5.40, together with the lecturing and assessment design.

In accordance with this design, evaluation sessions were undertaken at Middlesex University Malta, with final-year undergraduate students studying Computer Science and Information Technology. Participants were chosen using a purposive sampling from enrolled students within an Artificial Intelligence module. 48 students volunteered for this study, which ranged between the age of 19 to 31, and the evaluation session was aptly scheduled to coincide with the curriculum delivery of the search-spaces concepts within AI lectures. To mitigate the potential bias introduced from prior study or work experience from students on search-spaces, a differential evaluation methodology was adopted (Catala *et al.*, 2011; Skulmowski and Rey, 2017). Hence, to obtain an individualistic baseline for eventual assessment of knowledge gain within participants, a pre-session examination on conceptual search-space knowledge was undertaken by all students prior to tuition using the evaluation questions attached in Appendix B.5.

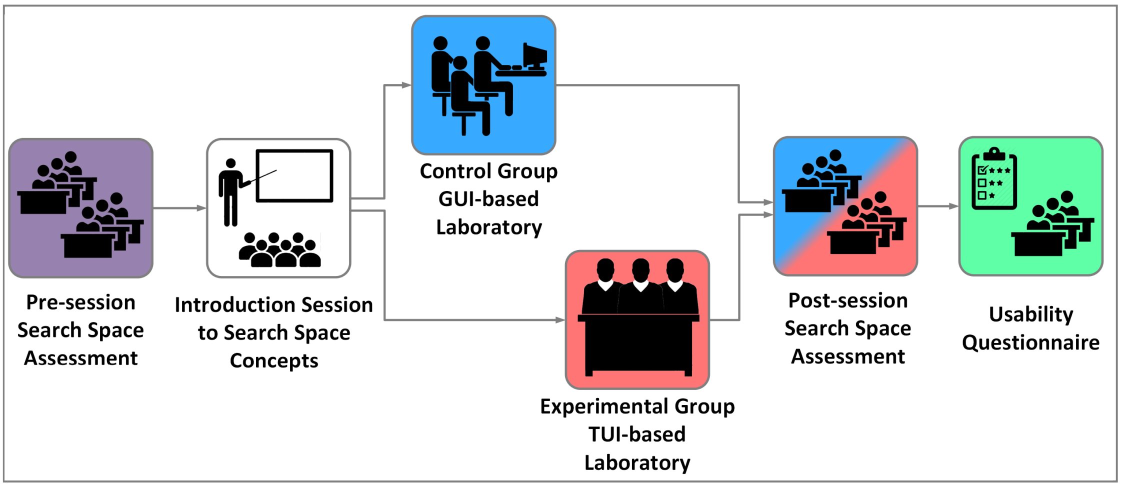


Figure 5.40 Evaluation stages designed for assessing the suitability of educational approaches for search-space concepts

Adopting a seminar/laboratory approach for tuition, the students were randomly split into groups of six and undertook a short introduction to the concepts of search-space exploration as well as given instruction on the aim and rules of the investigated river-crossing problem. To ensure uniformity and reduce experimental variables, this traditional lecture was conducted by the same lecturer for each group and a set of identical slides used to ensure the same content delivery is provided in each session.

As illustrated in Figure 5.40, students were subsequently randomly split into two groups of three students which constituted the experimental and control groups for the laboratory assessment. The intended design variable within the evaluation methodology was to utilize a different educational technology. Thus, whilst the experimental cohort explored the search-space of solving the *Japanese family river-crossing* puzzle via the proposed tangible approach, the control group utilized a web-based educational software for an identical puzzle which is optimized for GUI-based interaction (JapaneseIQTest, 2015). The latter were also provided with additional laptops as well as pen-and-paper facilities to record and analyse search-space states whilst exploring. This ensured that both cohorts had equal ability to derive and evaluate the search-space for the contextual problem.

Following a 20-minute laboratory session delivered sequentially as illustrated in Figure 5.40, both groups were once more assessed with a set of open-ended examination questions, which covered the same theoretical and practical knowledge as the pre-test assessment but adopted different questions, shown in Appendix B.5.3, to mitigate influential-bias from the prior assessment.

5.6.4 Results Analysis

The examination questions were assessed against pre-defined marking schemes and grades were correlated for each individual student making use of unique student identification. The performance of each cohort was subsequently averaged and tabulated in Table 5.1. Analysed under an independent sample t-test, the pre-test grades showed no significant statistical difference ($\rho > 0.23$) between control and experimental group of students outlining the suitability of the randomized allocation methodology.

Table 5.1: Assessment Grade Analysis

	Assessment Grades				
	Pre-Session	*Post-Session*		*Knowledge Gain*	
	All	*GUI*	*TUI*	*GUI*	*TUI*
mean (μ)	10.9%	46.7%	85.1%	38.1%	71.9%
std dev (σ)	13.5%	18.9%	11.0%	17.5%	14.3%
Sample Size (N)	48	24	24	24	24

	Knowledge Gain Difference				
	Mean (μ)	*Std Dev (σ)*	*p-value*	*test statistic*	*DoF*
Paired t-Test	33.8%	20.3%	0.0001	8.32	24

As can be visualised from Figure 5.41, control group students who engaged with the web-based GUI software obtained a knowledge gain of 38.1% (σ: 17.5) when comparative grades are analysed under a paired sample t-test at a 95% confidence level ($\rho < 0.001$). In contrast, the experimental group students who undertook the same search-space exploration puzzle obtained significantly higher grades as listed in Table 5.1. Thus, the proposed tangible approach provided students with an average knowledge gain of 71.8% (σ: 14.2, ρ <

0.001), illustrated in Figure 5.41. As detailed in Table 5.1, the improved conceptual understanding of search-space exploration principles brought about by the proposed tangible educative approach was confirmed using an independent sample t-test on the individual knowledge gain grade differences which highlighted the statistical difference of the 33.8% (σ: 20.3) improvement ($\rho < 0.001$).

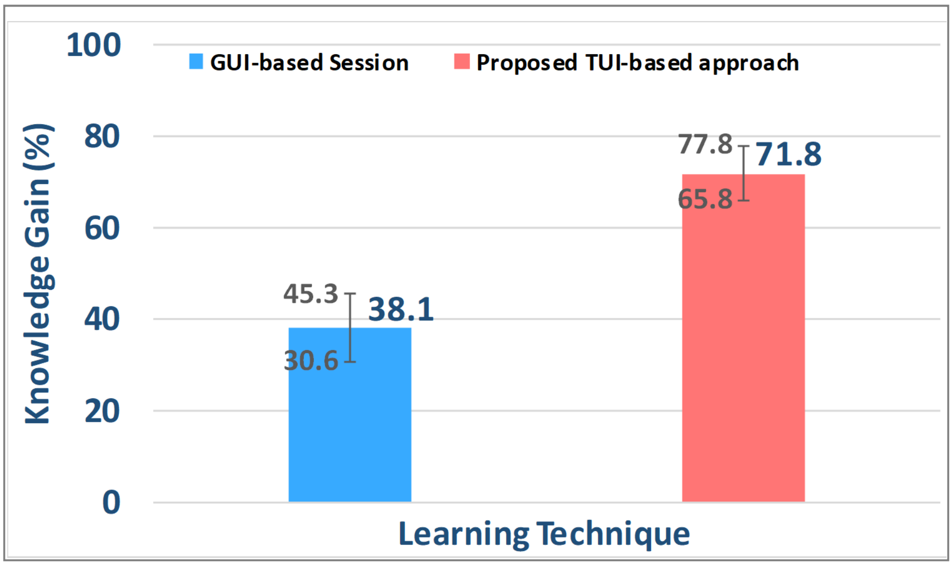


Figure 5.41 Relative grade improvement obtained by students with 95% confidence levels following both educational sessions respectively.

Analysis of the search-space exploration done by each group of students further outlined that the experimental students evaluated a wider search-space coverage through the TUI framework in comparison to the control group. This exploration density was analysed for both educational approaches in accordance with the following hypothesis:

- **Null hypothesis** (H_0): the means of state-space coverage are the same
- **Alternative hypothesis** (H_1): there is a statistical significance between the TUI and GUI state-space coverage means.

The exploration data was statistically analysed using a Welch two-sample t-test, which compensated for the limited sample size and adjusted the degrees of freedom accordingly to mitigate this potential statistical bias. This test allowed for a direct comparison of search space exploration undertaken by each of the six groups of four participants on either technology. The results highlight, at a 95% confidence statistic (ρ <0.001), that the experimental group undertook an average search-space coverage of 8.1% (σ: 1.7) in contrast to the 3.3% (σ: 1.3) done by the control group. The extent of this search difference was outlined by an estimated effect size (Cohen's *d*) of 2.85 as shown in Figure 5.42, yielding a confidence power value of 99.8% for the observed effect. The significance of the t-test power value outlines the probability of observing a real effect from the given data, reducing the probability of a Type II error in incorrectly determining the null-hypothesis of having equal knowledge gain.

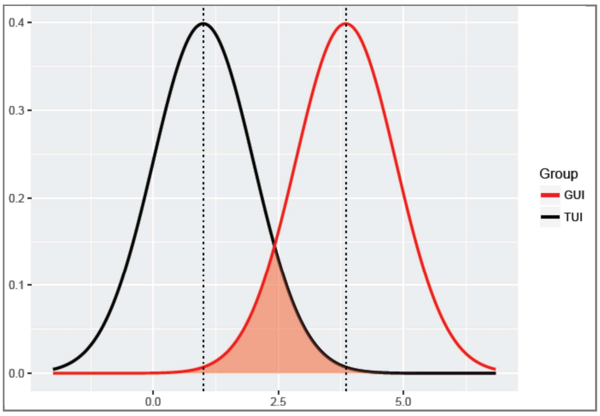


Figure 5.42 Distribution plot for both experimental groups. The Effect Size (Cohen's d) is the distance between the 2 means (shown in dashed vertical lines).

To ascertain the meaningfulness of this additional search-space exploration by TUI-based interaction, the developed software was designed to log every individual action and state investigated by users. This approach directly digitized students' timed progress for analysis without requiring manual data input. The proposed hypothesis investigated H_1, was therefore that a more meaningful exploration was undertaken through the tangible approach constituting of a mixture of breadth-first search and depth-first search methodologies through the state-space. To quantitatively evaluate this hypothesis, a direct comparison was undertaken for the sequential actions of each student group as visually aggregated in Figure 5.43.

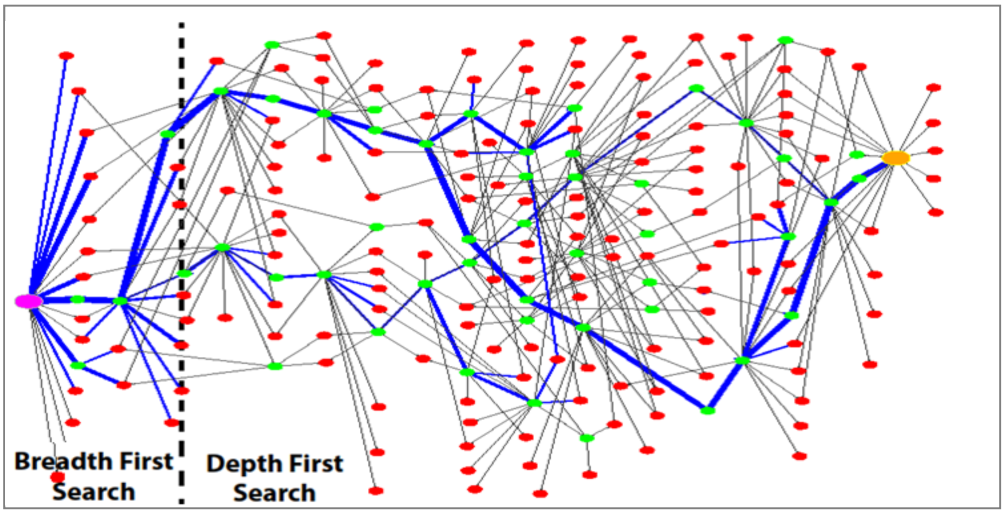


Figure 5.43 Search-space exploration undertaken by TUI-based interaction (blue edges). Edge thickness indicates the number of students exploring that path. The start node is shown in pink, valid states in green, invalid states in red, and the goal state is depicted in yellow.

The comparison was computed against a random/blind search approach, which, simulated through a hill-climb algorithm, considered each action based on the next best available state change using a heuristic derived from the number of persons transported across the river to score each state (Jarušek and Pelánek, 2012). At each time instant, the selected students' moves were algorithmically compared to a hill-climb approach over a short time-window of the next 10 moves, and the path similarities were measured using the Levenshtein distance metric. This measure of similarity was adopted for its appropriateness to compare and quantify the distance between search move strings by each group. So as to statistically quantify the cumulative distribution of the student data with respect to the reference hill-climb function distribution, a two-sample Kolmogorov-Smirnov test was performed. The test result on the proposed hypothesis, obtaining a test statistic of D=0.2 at 95% confidence level (ρ < 0.001), thus disproving the H_0 null-hypothesis. This result underlined the meaningful interaction and exploration undertaken through the TUI system, which as shown in Figure 5.43, visually illustrates that a broad breadth-first search was largely undertaken by students prior to subsequently selecting a depth-first search towards the solution.

5.7 Object-Oriented Programming

The focus on computational literacy and coding skills has grown substantially over the past years with an increasingly wide audience of learners shifting interest from computer and ICT applications towards rigorous computing, programming and problem-solving skills (Hubwieser *et al.*, 2014). Within today's information society, the ability to express and solve complex problem-solving in computational form, defined by Wing (2006) as *Computational Thinking,* is often considered an essential prerequisite for all students studying at higher education. This thinking perspective covers a broader spectrum than just programming and includes a range of mental tools that reflect fundamental computer science principles and concepts; such as abstracting and decomposing a problem, generalizing solutions and being able to identify recurring patterns (Malizia, Turchi and Olsen, 2017). This algorithmic thinking benefits not only domains of mathematics and science, but research has also outlined the importance of programming education in language skills, social-emotional interaction and creativity (Clements, 1999).

To this end, long-standing research has solidly outlined pedagogical principles underlying programming education (Goschnick, 2018). From a *constructivist* pedagogical perspective, learning programming curricula are often designed as a construction process, where students gradually build new knowledge and programming structures on their fundamental understanding of computational instructions (María *et al.*, 2006; Harper, 2010). Furthermore, from an experiential learning paradigm, Kolb's learning cycle theory (Kolb, 1984), fundamentally underpins the effective teaching and learning lifecycle of programming activities. In this context, students often develop their programming understanding through the cyclic processes of; practical code development (*active experimentation*), code compilation and execution (*concrete experience*), gathering and reflection on execution results or compiler errors (*reflective observation*) and finally extraction of conclusions from information analysis (*abstract conceptualization*) commonly leading to further epochs of debugging or active experimentation with programme execution (Rodríguez Corral *et al.*, 2014).

Notably however, students often experience difficulties when trying to understand the abstract object-oriented programming (OOP) concepts of; classes, objects, encapsulation, attributes, inheritance and polymorphism (Kölling, 1989; Sheetz *et al.*, 1997; Sivasakthi and Rajendran, 2011; Olier Quiceno, Gomez Salgado and Caro Pineres, 2017). Investigating these principles, research efforts commonly record conceptual misconceptions and difficulties within students (Miller, Settle and Lalor, 2015), often attributed to the abstracted nature of concepts which are difficult to relate equivalently in real life (Yan and Lu, 2009; Xinogalos, 2015). Albeit being intrinsically inspired by natural thinking processes of object properties and behaviours, students often struggle to undertake a mental-shift between procedural and object-oriented paradigms of problem-solving (Kölling, 1989; Lokare, Jadhav and Patil, 2018). This phenomenon is even more pronounced with students initiated in imperative programming, who conservatively attempt to retrain their traditional view of constructing computational instructions through procedural and flow control structures as an alternative to learning the new threshold concepts (Overmars, 2005).

Rodríguez Corral *et al.* (2014) further outlines that traditionally teaching programming as the creation of text-based programs provides students with neither attractive or familiar environments since most students are well experienced in the use of graphical computing environments (WIMP / gestural interfaces) rather than command line (textual) interfaces. Research efforts have thus recently arisen towards providing graphical programming environments towards introducing computational thinking to a wide audience of learners (Morrison, 2015). Through block-oriented programming approaches, tools such as *Scratch* (Resnick *et al.*, 2009), *Blocky* (Fraser, 2015), *Code.org* (Kalelioğlu, 2015) and *App Inventor* (Wolber and Abelson, 2011) allow students to compose algorithms through visual logical blocks. Moreover, tangential research paradigms integrate game-based learning designs which engage students in computational thinking and programming activities through the use of educational computer games (Prensky and Marc, 2003; Chen and Cheng, 2007; Seng and Yatim, 2014).

5.7.1 TUI in Programming Education

The introduction of post-WIMP interfaces such as TUI frameworks provide a compelling way to help students grasp abstract concepts whilst developing computer thinking skills (Wang, Wang and Liu, 2014; Turchi and Malizia, 2016). Interweaving digital computations with the physical interactive paradigm, educational TUI frameworks provide students with the opportunity to solve computations problems by logically manipulating objects in the real world which directly generate and compile programming code logic (Fernaeus and Tholander, 2006). This tangible affordance lower's the threshold barriers for children to learn programming (McNerney, 2004; Sapounidis, Demetriadis and Stamelos, 2015), as well as facilitate the creativity and concretization of symbolic and abstract manipulations in computational thinking (Cassell, 2004; Horn, Crouser and Bers, 2012). As evaluated by Sapounidis and Demetriadis (2013), through careful design, tangible programming frameworks provide a more fun and enjoyable interaction paradigm for users, which sustained research over the past years in developing TUI architectures for teaching programming skills to younger children.

Arguably the first tangible programming interface to be developed was *Button Box* (Perlman, 1974)*,* which enabled children to control a “floor turtle” through a subset of Logo™ commands called *TORTIS*. Whilst succeeding in providing a facilitating approach towards programming interaction, this system provided no way for children to modify a program once it has been created and thus was limited in its ability to accommodate experiential learning. This pioneering work inspired several TUI architectures to be proposed in literature furthering the aim of introducing programming and computer thinking skills to learners (Papavlasopoulou, Giannakos and Jaccheri, 2017). *Kinetic memory* TUI architectures such as the *Topobo* system (Raffle, Parkes and Ishii, 2004) and *Dr. Wagon* (Chawla *et al.*, 2013) provide a customisable tangible programming tool which can record, interpret and playback programmed motion through tangible manipulation in stretching, twisting and pushing physical robotic components. Whilst these architectures support toddlers in scientific learning through interfacing between math and science ideas in dynamic system behaviours, the programming elements are highly abstracted and fail to aid older students in understanding and manipulating underlying logic and computations.

The interaction of digital information through physical tokens led to various TUI architecture designs to provide a tangible approach to block-oriented programming environments. Through the use of tangible modification cubes, *Tangicons 3.0* (Scharf *et al.*, 2012) provides an educational problem-solving framework for children whereby characters are virtually moved on a computer screen map based on the sequential steps defined through the ordering of multiple cubes. A similar game-based setup with wooden tiles was adopted for primary students in *Strawbies* (Hu *et al.*, 2015) which by integrating a tablet app provides students with the ability to design a real-time tangible programming game. Touretzky (2014) proposed a more advanced game-based TUI programming framework, whereby through physical *'tiles'*, students lowered their interaction barrier for understanding event-based concepts through the GUI programming game engine *Kodu* (Fowler, Fristce and Maclauren, 2012).

This framework integrated a *token-constraint* architecture, as also adopted within the *Tern* TUI programming setup (Horn, Solovey and Jacob, 2008), whereby physical interlocking jigsaw blocks aid students understand syntactic constraints whilst reducing the possibility of programming errors. Whilst these setups have outlined a facilitated learning curve for children in both museum and classroom learning environments, their development lacked the design integration for collaborative TUI interaction. The provision for distributed programming learning experiences was emphasised in the design of *Blinky Blocks* (Kirby, Ashley-Rollman and Goldstein, 2011), whereby a set of distributed units integrated with a developed Meld GUI programming language. Exploiting collective interaction, *TanProStory* (Qi *et al.*, 2015) introduces an object-oriented programming approach for primary children to tangibly engage with a storytelling scenario through the physical embodiment of story characters. Embodied learning is similarly adopted in the *Digital Dream Lab* (Oh *et al.*, 2013) TUI framework whereby a simple range of concepts relating to clustering and data manipulation has been successfully introduced using tangible manipulatives to children under five years old.

A variety of tangible architectures further extended block-based learning by physically integrating with robot-based programming setups. TUI systems such as *E-block* (Wang, Zhang and Chen, 2013) and *Robo-Blocks* (Nusen and Sipitakiat, 2012) provide primary school children between the ages of five to twelve years, the ability to program robot commands through the physical manipulation of tangible blocks in control instructions including branches, loops and subroutines. The engaging and enjoyable aspects of these architectures further provide an enhanced *constructivist* approach whereby students can reflect on the physical layout of their designed algorithm and tangibly debug and manage processes more effectively (Nusen and Sipitakiat, 2012).

Implementing *token-constraint* tangible affordances, *CHERP - the Creative Hybrid Environment for Robotic Programming* (Strawhacker, Sullivan and Bers, 2013) adopts interlocking blocks to guide onscreen programme development. The architecture passively tracks the arrangement of iconic blocks indicating robotic instructions and control flow blocks which are subsequently downloaded onto robotic artefacts (Strawhacker and Bers, 2015). TUI Developments for kindergarten and young children have also successfully introduced basic problem solving and computational learning skills through tangible robotic playsets like *Cubetto* (Mariappan *et al.*, 2017) and *TanProRobot* (Wang *et al.*, 2015). These architectures capitalise on block-based programming through differently coloured or shaped blocks to allow children to programme physical playful robots with movement instructions and sensor parameters (Wang *et al.*, 2016). The tangible robotic architecture in *RoboStage* (Chang *et al.*, 2010) furthers the deployment with the deployment of mixed-reality interaction to introduce event-handling and task-solving to children whilst effectively engage with robotic interactions in concrete experiences and collaborations.

The development of tangible robotic kits, further merged constructivist pedagogies by providing children with the ability to construct and configure their physical robots, Through tangible programming environments such as; KIBO (Sullivan, Elkin and Bers, 2015) and *Quetzak* (Horn and Jacob, 2007) students are provided the opportunity to construct robotic artefacts using a range of motors, sensor and materials which are subsequently programmed through tangible tiles which configure and alter sequence, loops and parameter variables through physical flow-of-control chains. These architectures notably extend the *LEGO Mindstorms*™ robotic toolkit (Martin, 1995), introducing a tangible and collaborative environment for students to learn programming concepts.

The deployment of *constructive assembly* TUI architectures like *Programming Bricks* (McNerney, 2000) and *littleBits* (Bdeir, 2009), further embody tangible and digital interaction through the use of active programming blocks. These functional elements, electronically assembled through magnetic connectivity, provide children with the capability to intuitively alter computational parameters as well as construct elaborate instructions by physically combining tiny circuits and interactive devices (McNerney, 2004).

As concluded in the research investigation by Papavlasopoulou, Giannakos and Jaccheri (2017) albeit providing an easier and more enjoyable approach towards engaging children with programming concepts, need still exists to formally evaluate the teaching and learning effectiveness of TUI programming frameworks in school classrooms. An analysis of TUI deployments for programming education further outlines that whilst reducing the threshold for engaging with coding, educators commonly find difficulties in providing a deep understanding of the underlying concepts since frameworks often restrict the improvised, iterative, and experimental exploration of concepts due to technological expandability constraints. Thus, with the exception of the work by Vidarte et al. (2010), which aimed to introduce recursion and functional programming through a tangible augmented reality mixed-interface, programming TUI frameworks have mostly targeted simplified programming concepts such as; computational parameters, Boolean logic, control-of-flow chains and event-based programming. Furthermore, the TUI frameworks reviewed in literature have been mostly confined in educational focus towards kindergarten or primary children, thus abstaining from delivering conceptually complex and abstract notions embedded within learning object-oriented programming.

5.7.2 Object-Oriented TUI Framework

In contrast to the contributions from previous literature, this section proposes the design and development of a TUI framework for teaching and learning abstract programming concepts in HEIs. Specifically, addressing the difficulties encountered by HEI students when learning object-oriented programming (OOP), the designed framework presents an interactive educational tangible platform to introduce concepts such as; *abstraction*, *inheritance,* and *instantiation*. To this end, a set of design requirements were elicited from HCI literature and computer science academic practitioners to define guides for the design and development of the proposed TUI framework as enlisted hereunder:

- **Learnability –** Through the design of intuitive user interactions, the TUI framework should reduce the extraneous cognitive load needed for students to engage with the educational technology.

- **Accessibility –** The system functionality must address both HEI students who are at the beginning of their programming studies as well as aid advanced users with a priori programming experience in overcoming the complex and abstract attributes underlying OOP threshold concepts.
- **Focus and Attention -** The system must lead users to dynamically interact with the tangible framework by naturally guiding attention and focus on the displayed information in an orderly manner.
- **Efficiency –** Interaction design should intuitively guide students towards achieving their learning outcomes at their own learning pace with little or no supervision.
- **Real-world representations –** The system should employ representational models of familiar contextual objects to aid students associate and concretize conceptual knowledge through embodied cognition.
- **Usability Satisfaction –** Integrating real-time feedback through haptic and graphical cues, the TUI framework should enable users to seamlessly progress from one computational task to another.
- **Effectiveness –** Through a variety of multi-modal representations including visual, audio and tactile interactions, the TUI design should enhance support to constructivist and experimental learning.

5.7.2.1 Tangible Design

To this end, a tabletop TUI architecture, as detailed within chapter 4 was incorporated within the proposed framework in line with the appropriate physical designs for interaction by HEI students. This setup was extended further through the integration of an Arduino Mega^{TM} microcontroller which via the control of electronic components such as LEDs and servo motors enabled the deployment of smart peripherals on the TUI architecture as detailed in section 4.2.4. These modular components enabled the proposed framework to augment the tangible paradigm interaction through the use of dynamically controlled placeholders and revolving platforms which provide the TUI design additional behavioural-change triggers.

A contextualisation scenario was also designed for introducing the abstracted OOP concepts using a familiar analogy through vehicle-based examples. The intrinsic familiarity of students with understanding and constructing conceptual notions on real-life vehicles provided an ideal context to aid explaining the underlying notions. Thus, fundamental OOP concepts such as *objects*, *attributes*, *functions* and *abstraction* were associated with relatable vehicle properties as pictured in Figure 5.44.

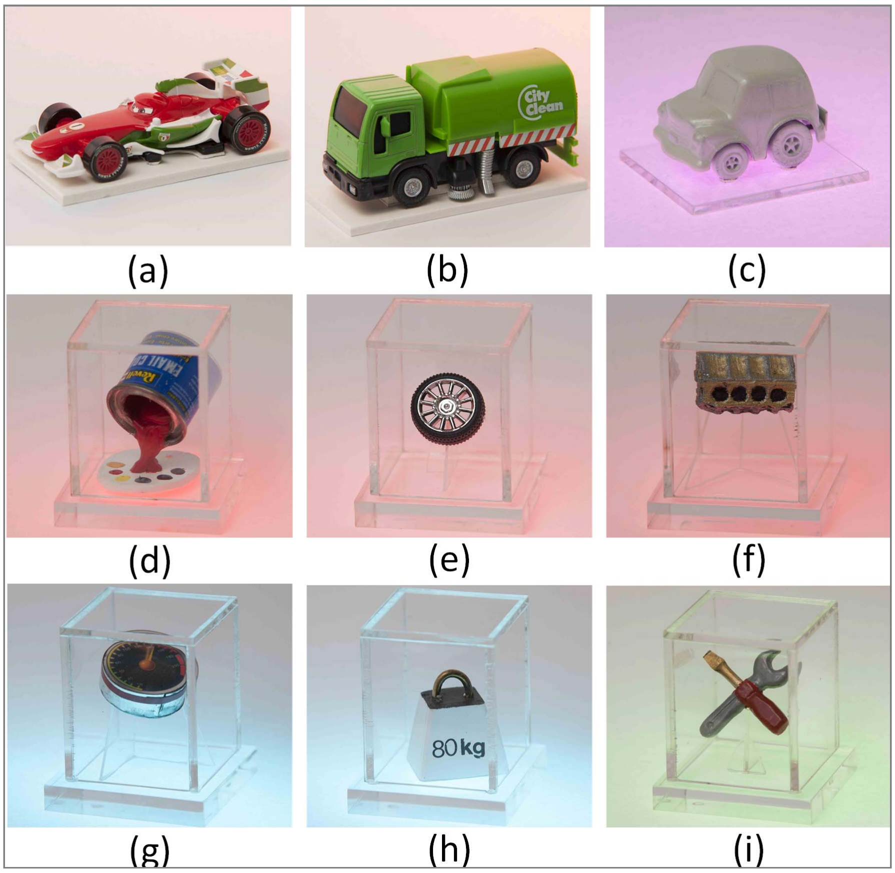


Figure 5.44 OOP designed tangible objects contextualized for vehicle notions;

a) Racing car - object, b) Truck – object, c) Vehicle – abstract class,

d) Paint colour palette – attribute, e) Wheels – attribute, f) Engine – attribute,

g) Speedometer – function, g) Load carrying – function, g) Service – Attribute/Function adjustment.

The design of these tangible artefacts took into consideration several as aesthetical aspects (Fontijn and Hoonhout, 2007), to stimulate the innate recognition and embodied cognition of abstract OOP conceptual elements as elucidated in the following systematical descriptions:

- Objects – Figure 5.44(a)-(b): Models of a racing car and truck were selected to exemplify tangible objects within a vehicle-based conceptual understanding. These objects were designed to elicit an inherent familiarity to users, thus embodying a subset of abstract properties and functionalities towards each representation.
- Attributes – Figure 5.44(d)-(f): 3D models of objects symbolising common vehicle elements and properties were designed within the TUI framework to conceptualise the notion of attributes in OOP design. Two identical sets of tangibles were developed which allowed students to dynamically allocate each generic attribute towards distinct conceptual objects.
- Functions – Figure 5.44(g)-(h): The use of a speedometer and load models provided students with the ability to conceptualise abstract functions commonly associated with vehicles. These tangibles were designed to intrinsically reflect the distinct capabilities of each conceptual object and thus provide students with the ability to engage with different OOP methods.
- Abstract Class – Figure 5.44(c): The design of an abstracted class concept was represented within the proposed framework through the 'featureless' model of a vehicle. The distinctive nature of this model allowed students to concretise the abstracted characteristics of this notion whilst interacting with the deployment of abstract class inherence within OOP design. This tangible was also affixed underneath with a neodymium magnet which allowed for seamless attachment and detachment from the peripheral revolving platform.
- Adjustment – Figure 5.44(i): The use of a vehicle service symbol was designed within the illustrated tangible to provide the capability to

configure and adjust object elements in designing an OOP solution. Hence, by means of this tangible, students were afforded the capacity to physically alter elements within their OOP design in the customisation of an inherited vehicle class.

To help students discriminate tangible manipulatives representing between concrete elements (such as objects and classes) and intangible notions (such attributes and functions), the latter were enclosed in a clear acrylic casing. Whilst providing physical protection for the design of more elaborate representations of these abstracted aspects, the enclosure embodied a further cognitive design aspect, whereby students were physically restricted from touching these abstruse models whilst still perceiving their existence and interactive effects. Moreover, the translucent casing designed within these tangibles enabled the proposed framework to digitally and dynamically assign these properties onto individual objects by illuminating the objects with a coherent colour schema as illustrated in Figure 5.44(d)-(i).

As shown in Figure 5.44, each object was mounted on an acrylic platform (6cm x 6cm) and the dimensions of tangible device restricted to a height of 7cm. This was designed to enhance the usability and comfortable interaction for students, whilst at the same time occupying a minimal spatial area on the interface to increase the available interactive area for virtual projected information. Underneath each tangible, a unique reacTIVision ‘amoeba’ fiducial was attached (Bencina and Kaltenbrunner, 2005), which allowed the simultaneous optical tracking and identification of multiple objects on the interactive tabletop architecture. Furthermore, the rotationally variant nature of these monochromatic symbols allows the proposed TUI framework to identify the rotational angle of each manipulative, thus augmenting their spatial and translational domains of interaction.

5.7.2.2 Tangible Interaction Design

The proposed TUI framework embedded digital information through an interweaved GUI that provided a cohesive and intuitive interactive setup to teach and learn abstracted OOP concepts. This element was developed in Java whilst integrating a TUIO client for tangible communication and a JSSC library for interfacing with the active Arduino™ components of the architecture. Careful design considerations were also implemented within the graphical images employed within the TUI framework as to provide a coherent and contextual mapping for students thus reducing their interaction cognitive load. As illustrated in Figure 5.45, a set of representational images were designed to visually reflect the various tangible artefacts.

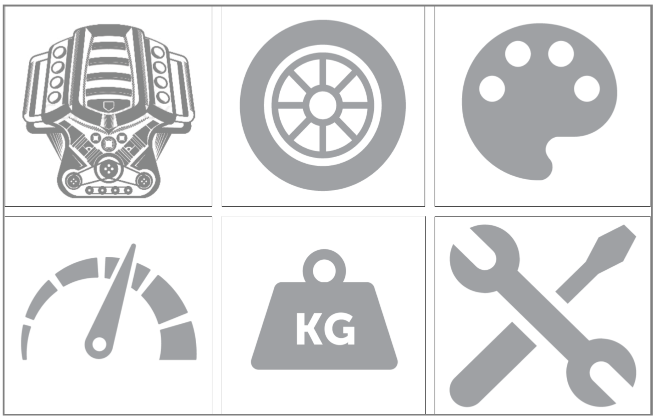


Figure 5.45 Design of graphical representations for coherent tangible coupling.

These were physically printed onto distinct peripheral placeholders, which through active integration with controlled LED lighting cues enabled the TUI framework to guide students in placing or removing tangibles onto the interactive surface. Furthermore, to strengthen the multimodal coupling whilst provide real-time feedback to users on tangible interaction, these images were digitally projected underneath tangibles once detected and identified through the TUI framework as shown in Figure 5.47.

Students were further guided through tangible interaction through the use of digital silhouette placeholders, as depicted in Figure 5.46, that were dynamically projected in fading animation on the interface. These digital cues where coupled with tangible feedback through the pulsating illumination of respective physical tangibles cohesively aid to reduce the extraneous cognitive load imparted on students when interacting with the TUI framework. Furthermore, the silhouette images for each vehicle, as distinctively outlined in Figure 5.46(a)-(b), introduced students through a colour coded schema for discriminating interaction with either OOP object. Through these design considerations, students are further able to feel in control of their interactions and require less external assistance in successfully engaging with the educational system.

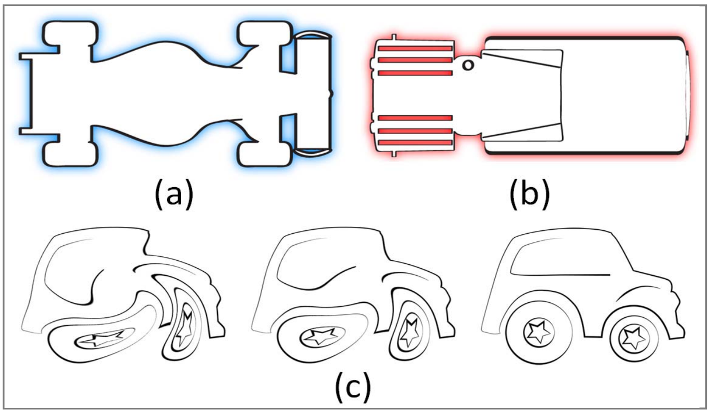


Figure 5.46 Graphical placeholder animations for guiding TUI interaction. Images resemble used tangible objects to facilitate user intuition whilst indicating the completion status of the conceptual classes.

As highlighted within the graphical interface in Figure 5.47(a), students are provided with an unconstrained interaction space to interact with the conceptual understanding of class abstraction. Through this interface, students can elicit the various attributes and behaviours associated with each OOP object and simultaneously physically allocated respective tangibles on the tabletop interface. Through the spatial identification afforded from optical tracking, the TUI framework allows students to undertake epistemic actions in manipulating and spatially organising their solution design. Moreover, the tangible interface provides the provision of proxemic interaction between tangibles, which are digitally interlinked together by means of a sinusoidal waveform animation once within a radial distance from an object entity. This illustration provides users with intuitive real-time feedback on the performed interactions and facilitates the situational encoding through concretised computationally coupled interactions.

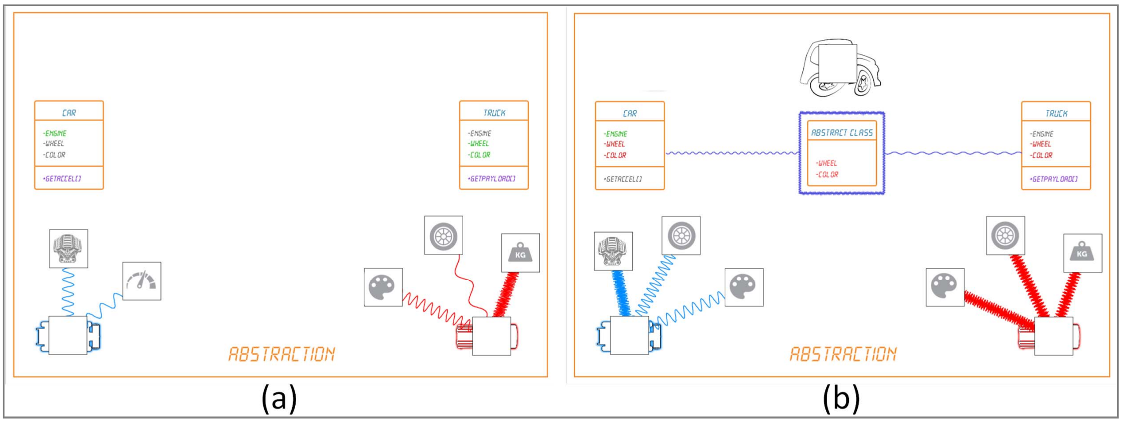


Figure 5.47 Graphical representations of tangible interaction in learning class abstraction concepts [6].

Furthermore, as illustrated in Figure 5.47, a digital UML-based class entity is projected in perceptual proximity of each OOP object, which is dynamically compiled as students define additional attributes and functions for each object. Through the use of colour coding, registered elements are highlighted within respective tables, showing the distinction between class attributes which are defined uniquely (green) and ones which are common between both sports car and truck objects (red).

Upon detection of identical attributes mutually placed on either object, the TUI framework introduces students to the notion of class abstraction by actuating the platform rotating servo to reveal a previously hidden tangible as pictured in Figure 5.48. The active tangible interaction designed within the TUI architecture pervasively directs student focus through a *'surprising'* effect towards the rotated abstract class tangible.

[6] Video clips of Multi-Threaded Scheduling TUI framework available on https://youtu.be/9IxlAK3QGxU

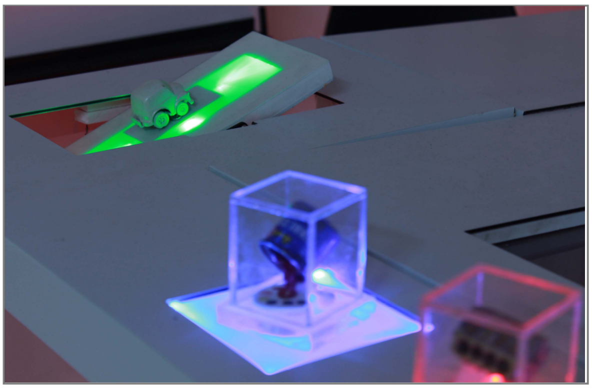


Figure 5.48 Rotating platform dynamically revealing the abstract class tangible.

In tandem to this interaction, a digital placeholder, captured in Figure 5.47(b), is illustrated on the upper section of the interactive surface, prompting the user to understand the possibility of defining an abstract class between both object instances. As illustrated in Figure 5.46(c), a sequence of images are progressively displayed as a placeholder for the abstract class tangible. These visuals are dynamically altered as students introduce more shared attributes between object attributes, thus graphically reflecting the enriched nature of the abstract class composition. Following the experimentation with different entity configurations for abstraction design, students are prompted through flashing LED lighting on the rotating platform to engage with the abstract class tangible through a magnetic detachment as shown in Figure 5.48. Upon placement on the interactive surface, as captured within Figure 5.47(b), a graphical animation is further interactively displayed to students, outlining the selected attributes in the composition of a UML-based entity descriptor for the abstract class. This visuospatial feedback is designed to engage students with reflective learning as the conceptual mapping is externalised through the proposed TUI framework.

In line with the constructive pedagogy of scaffold learning, following the understanding of *class abstraction*, students' progress at their own learning pace towards the introduction of *inheritance* and *instantiation* concepts by physically manipulating the abstract tangible on the interface. Once selected through translational tangible interaction, a staged approach is adopted within the TUI framework that allows students to understand the inherited class concepts through the visualisation shown in Figure 5.49(a). Within this interface, students are able to visualise the inherited class attributes and functions in a UML-based diagram, which is further enhanced through OOP code syntax for initialisation of values through a dynamically programmed constructor method syntax. Moreover, during this stage, students can engage in constructive pedagogies in altering the elements of the inherited class through the use of *'service'* tangible. As shown in Figure 5.49(a), this manipulative allows students to alter and add additional attributes and functions extending the generic *'car'* class experimentally. The addition of these elements is provided through graphical real-time feedback, whereby the selected attributes are reflected on the generic vehicle image through graphical additions of 'spoiler' and 'headlight' images. This is further complemented with a dynamic addition of code syntax on the GUI elements to allow students to understand the equivalent programming instructions, thus abridging the threshold transition between conceptual and practical understanding of OOP concepts (Fernaeus and Tholander, 2006).

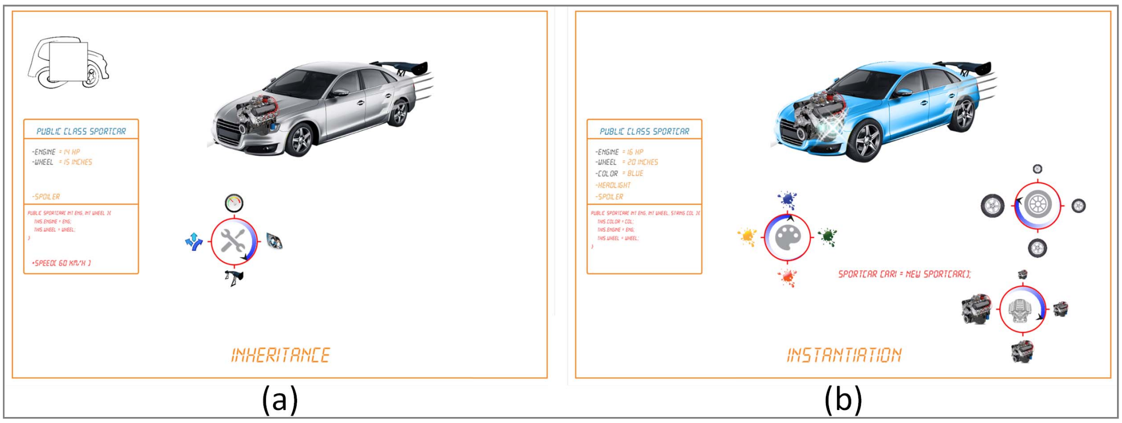


Figure 5.49 Graphical representations of tangible interaction in learning: (a) class inheritance and (b) object instantiation concepts.

Subsequently, students are prompted to interact once more with the abstract tangible to progress their learning phase by *instantiating* an object from the developed class. Within this interface, captured in Figure 5.49(b), students engage once more with the attribute tangibles to customise their object instance by experimentally altering the attribute values to design their desired vehicle. Tangible objects are digitally enhanced within the TUI interface during these stages by surrounding each physical object with a perceptually and computationally coupled rotational selection menu as shown in Figure 5.50.

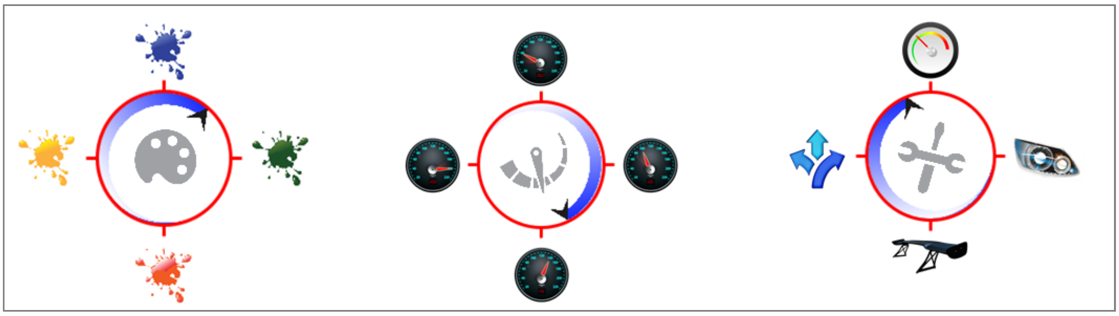


Figure 5.50 Digital rotational selection menu attributed to each tangible for parameter setting through physical interaction.

This representation provides students with the ability to rotationally interact with attribute and function tangibles through the digital projection of a rotating arrowhead which mirrors in the real-time angular placement of each manipulative. Thus, through the selection menu attributed to each component, students can customise the attribute parameters of the instantiated object. Furthermore, as shown in Figure 5.49(b), reflective understanding is provided through perceptual feedback on the dynamically altered vehicle visuals together with a concurrent change in the respective code syntax projected for the object development parameters.

The TUI framework design intrinsically designates the abstract class tangible as a fundamental controller within the algorithmic execution of the system, supporting students to experiment and reflect on their conceptual understanding in various problem-based scenarios. The functional execution is further reinforced through dynamic labelling for each OOP conceptual stage, together with synchronised interactive elements controlled through the active peripherals and digital representations. Thus, this interactive approach constantly provides the ability to alter between different stages of OOP conceptual elements, which aids to further solidify their working memory models as well as inherently understand the relational dependence between stages of OOP design.

5.7.3 Evaluation and Results

To evaluate the effectiveness of the developed TUI framework for teaching and learning abstract OOP concepts, the latter was deployed for evaluation at Middlesex University Malta within undergraduate degrees in Computer Science and Information Technology. Purposive sampling was undertaken to select 27 students studying the first-year module on '*Introduction to Java programming*' who voluntarily offered to participate in the evaluation study. The topic of object-oriented programming presents a threshold concept within the syllabus of this module and the evaluation session was coordinated to coincide with the formal introduction to OOP concepts in line with the module's scheme of delivery.

5.7.3.1 Evaluation Methodology

An evaluation methodology was implemented which was designed to yield a quantitative as well as observational analysis of the effectiveness of the proposed TUI framework in HEI integration. In line with the evaluation stages illustrated in Figure 5.51, all students were initially provided with a short introduction to the notions of object-oriented programming in line with a subset of lecture slides which introduced basic terminology and foundational principles. At the end of this brief tuition session, a pre-test assessment was undertaken on all students in relation to the delivered OOP concepts. This test was composed of seven (7) open-ended questions as shown in Appendix B.6.1. which covered a combination of theoretical, detail-oriented, and problem-based questions. Through the assignment of a unique student identifier, each transcript was thus employed as a knowledge baseline to assess the effectiveness of practical seminar sessions in aiding to overcome the cognitive barriers in learning this threshold concept.

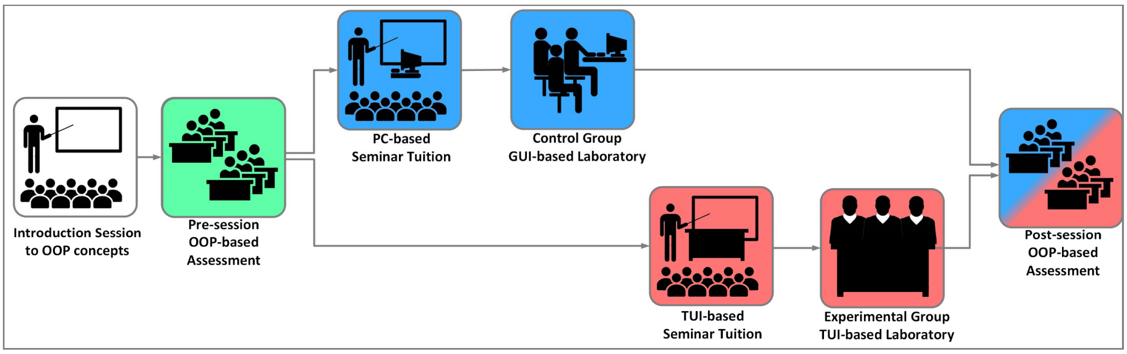


Figure 5.51 Evaluation methodology designed for assessing the suitability of the proposed educational TUI framework with respect to PC-based programming for teaching and learning OOP concepts.

Following this assessment, students were randomly split into two quasi-equal groups for their seminar and laboratory sessions. Serving as an experimental control, a group of twelve (12) students attended a traditional seminar whereby OOP concepts were exemplified through the use of a conventional Integrated Development Environment (IDE) which was projected on an affixed smart-board. Conversely, an experimental group of 15 students attended a similar seminar session within which the use of the proposed TUI framework was adopted by the lecturer to explain the same OOP concepts. To reduce the potential of experimental bias, both seminar instances were delivered sequentially by the same lecturer on the same day using an identical vehicle-based case example. Subsequent to each session, and to provide a fair comparative analysis with the a suitable group size for the PC-based control group, students were further divided into groups of three (3) and undertook a laboratory exercise on the respective educational technology which provided the opportunity to collaboratively experiment with the introduced notions of OOP design and development. This group subdivision size was designed so as to provide a fair comparative assessment with respect to the efficacy potential of collaborative work undertaken on PC-based technology which was utilised as the experiment control.

As illustrated in Figure 5.51, at the end of the evaluation cycle, each student was finally re-appraised on the acquired OOP knowledge through the use of a second assessment as shown in Appendix B.6.2. This examination was carefully designed to assess similar conceptual and practical knowledge on OOP principles whilst presenting students with a different set of questions to curtail bias from previous answers. This evaluation methodology thus enabled the quantitative assessment of knowledge gained by individual students through the provision of a seminar/laboratory session using either educational technology.

5.7.3.2 Results and Discussion

Equitable analysis on the marked grades for each student assessment was performed using statistical software (Kenneth and Babinec, 2017). Prior to undertaking relational analysis on student data, validation was performed on the random split conducted during the evaluation methodology so as to ensure no knowledge bias was present between student group allocation. An independent-sample t-test performed on the pre-test scores of each student showed that no statistically significant difference was present between groups at $\rho > 0.48$. Thus, through the acceptance of the null hypothesis, an unbiased comparative analysis could be safely performed on the obtained data to assess the learning and teaching effectiveness of the evaluated educational technologies.

The evaluation dataset, graphically represented in Figure 5.52, illustrates the obtained assessment grades by each student prior and post attending a seminar/laboratory session whereby the use of an educational technology was deployed to aid conceptualise the introduced notions in OOP. A paired-sample t-test comparing the grades obtained by every student in either group confirmed that both groups registered a statistically significant learning gain at $\rho < 0.01$.

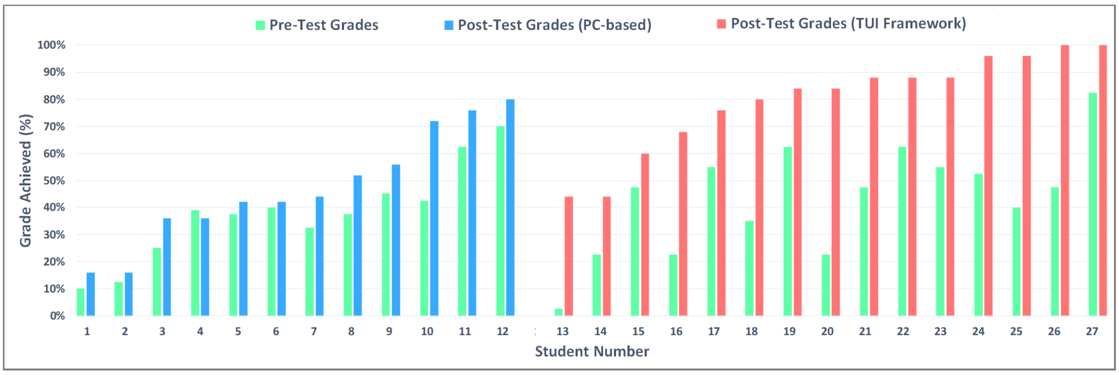


Figure 5.52 Student profile comparison of academic assessments prior and following seminar/laboratory sessions on OOP concepts using different educational technologies.

As shown in Figure 5.53, whilst the average grade improvement for the control group was that of 9.25% (σ: 8.1), the experimental group results illustrate an average grade increase of 35.5% (σ: 15.3) following interaction with the proposed TUI framework. The significance of this knowledge gain discrepancy between groups was further evaluated through the analysis of an independent-sample t-test. Under a Levene's test for homogeneity of population variances F(25) = 9.139, the analysis outlined a 26.5% (σ: 4.9) difference in knowledge gain between both technologies at a significance of $\rho < 0.01$.

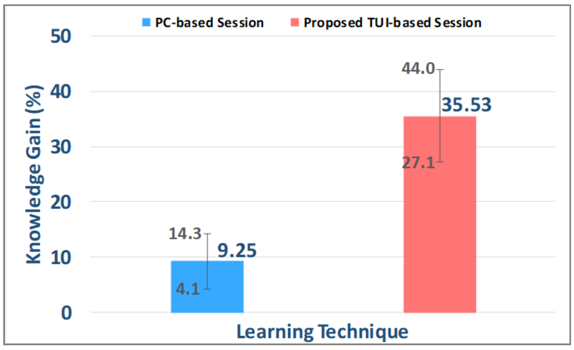


Figure 5.53 Relative grade improvement obtained by students with 95% confidence levels following conceptual OOP learning through different educational technologies.

As visually highlighted by the 95% confidence interval bounds on knowledge improvement attained through respective technologies in Figure 5.53, the designed TUI framework is able to pedagogically engage students in a more effective active learning process, thus facilitating their understanding of abstract and threshold concepts commonly experienced in OOP tuition.

This outcome was further consolidated through verbalisation and interaction analysis undertaken on video recorded sessions. This review outlined that students within the experimental group interacted more with the provided technology with respect to the control cohort which had notable difficulty in adapting their OOP conceptual understanding on a traditional PC-based IDE interface. Moreover, the collaborative design embedded within the TUI framework was also eminently observed, whereby groups using the tangible technology engaged in conceptually deeper and more focused discussions whilst navigating through the OOP laboratory exercise.

5.8 Artificial Neural Networks

In contrast to previous implementations in this study and within the literature, this section introduces a novel interaction concept within TUI frameworks by augmenting interactive surface architectures with active tangible manipulatives. This unique interactive paradigm presents TUI architectures with a smarter way to engage users and intelligently influence their scope of interaction. To further the limited successes identified in the literature on the of the efficacy of tangible systems in higher education, the proposed TUI architecture will be investigated for its ability to aid in the teaching and learning of abstracted Artificial Intelligence (AI) concepts such as Artificial Neural Networks (ANNs).

The section is organized so that a review of computer-aided techniques used to educate ANN is presented in section 5.8.1. The descriptions in section 5.8.2 outline the proposed smart interactions within an adapted TUI architecture from both a tangible and digital perspective. The obtained results from deploying the system within a university programme are finally presented and discussed in section 5.8.3.

5.8.1 Artificial Neural Networks

Within the domain of computer science, ANNs have quickly gained popularity as highly versatile machine learning algorithm with applicability in a myriad of applications ranging from image processing to autonomous control (Ishibushi *et al.*, 2015). Defined by (Caudill and Maureen, 1986) as; “a computing system made up of a number of simple, highly interconnected processing elements, which process information by their dynamic state response to external inputs”, this AI algorithm is further strengthened by feedback techniques such as back-propagation that provide a semi-supervised learning approach to optimize an output function convergence (Braspenning, Thuijsman and Weijters, 1995).

The ability of ANNs to address problems in classification, regression, time-series forecasting and complex system modelling (Ahmad *et al.*, 2014) has consequently made the tuition of this machine learning (MLA) algorithm a stable within computer science and engineering degree programmes (Díaz-Moreno *et al.*, 2016). Yet, despite its widespread adoption, the complex nature of the ANN algorithmic processes poses a common difficulty to teaching within HEI contexts, thus leading academics to often rely on application software packages to aid in the educational delivery (Ringwood and Galvin, 2002).

Amongst the most popular environments in use for this purpose are the *Waikato Environment for Knowledge Analysis (WEKA)* and *MATLAB*^{TM}, which allow students to process real datasets whilst makings use of prebuilt libraries and toolboxes (Díaz-Moreno *et al.*, 2016; Frank, Hall and Witten, 2016). Both platforms provide users the ability to pre-process, classify, cluster, associate, visualise and select attributes for given data. However, albeit these tools allow students to analyse the results of ANNs, their use is often overwhelming for inexperienced users and often hinders the student's abilities deeply learn the algorithmic processes.

Addressing the visualisation limitations above is commonly achieved through using bespoke educational software for ANNs. Applications such as *TensorFlow* allow students to interact with simulators online to allow customization of neural network architectures and visualise the obtained results (Smilkov and Carter, 2017). Similarly, the *Sharky Neural Network* application adopts animation aspects to introduce students to simulated process and adaptably visualise the obtained results (SharkTime Software, 2013). Whilst contributing to the visualisation aspects of teaching and learning ANNs, these packages however often lack technical flexibility. This limits the ability for students to experiment with operational parameters in order to conceptualize their understanding.

More adaptable platforms such as *Scikit-Learning* (Buitinck *et al.*, 2013) and *Theano* (Theano Development Team, 2016) allow students to easily set up and customize neural networks by making use of implementation libraries. Packages such as *Pylearn2* (Goodfellow *et al.*, 2013) and *Pyevolve* (Butterfield *et al.*,

2004) further extend ANNs with other MLAs, such as genetic algorithms, to extract further analysis from the obtained data. Comparably, the *Caffe* package facilitates the adoption of ANNs in image datasets and allows for the development of neural network architectures for detecting and classifying objects within images (Jia *et al.*, 2014). The technical capabilities of these applications however often technically overburden students with significant coding requirements and thus limits their ability to properly comprehend the underlying concepts of the ANN algorithmic process.

To this end, learners often resort to audio-visual media for studying the complex operational details of such algorithms, seeking educational channels on YouTube (YouTube, 2017) and virtual learning platforms to provide explanations and video-led examples (Poulson, 2016). Nevertheless, the sole use of diagrammatic representations and narration to explain the ANNs concepts, is functionally tantamount to the traditional lecturing approaches adopted within HEIs, which active learning pedagogies aimed to explicitly replace and augment using more engaging approaches.

5.8.2 Active Tangible Framework

In light of the above limitations to adopt educational technologies in this fundamental AI technique, this section provides a contribution to enhance in the teaching and learning of abstract concepts, such as those present in ANNs, using a real-time interactive educational tangible platform. Furthermore, in distinction from the current literature on TUI systems, this section proposes a novel interaction paradigm achieved by adopting active tangible manipulatives on an interactive surface architecture. This smarter technology is developed to help mitigate the peculiar challenges and augmented conceptual complexity experienced within HEI environments.

5.8.2.1 Active Tangible Interaction

In contrast to previous developments, the proposed TUI framework in this section presents an innovative interactive engagement paradigm to students by yielding an additional domain of user interaction through a set of active 3D physical objects. These objects were adapted by the TUI framework to allow the real-time design and configuration of neural network topologies as well as their operational parameters. The altering of these digital parameters using physical manipulatives is a central concept to TUI systems and hence a fundamental objective was to provide students with a heightened sense of intuitiveness and familiarity with tangible objects, thus reducing the barriers of interactivity commonly experienced by mature HEI students.

The active tangible concept was developed by embedding tangibles with autonomous computational architectural units that communicate wirelessly with a central processing server. To this end, within the base of each tangible object, an Arduino Nano™ was integrated, together with a small LiPo battery and a Bluetooth® communication module. This bi-directional communication architecture enabled each tangible object to independently transmit and receive data from the server processor via a serial communication protocol. To enable the optical recognition of objects by the computer-vision toolkit, a unique 'amoeba' marker (Bencina and Kaltenbrunner, 2005) was attached underneath each object. This provided the framework the capability to passively track and intelligently control active components within tangibles. Furthermore, this approach introduced real-time multichannel user feedback through passive computer-vision and active tactile/analog interaction.

To aid in the teaching and learning process of ANN concepts, a 'horse-racing analysis' contextual example was adopted to explain the artificial intelligence algorithm. This context simulated the relational model of horse race time based on parametrical data of speed and health. The selection of this domain exploited the inherent familiarization and prior exposure of HEI students with the typical data of this application, hence perceptively reducing the cognitive load experienced by students whilst interacting with the novel framework. The aesthetic design and functionality of tangible objects were subsequently further adopted to symbolise and represent different ANN parameters ranging from input, hidden and output nodes as well as network parameters and configuration adapters. As pictured in Figure 5.54, these neural network concepts are innately expressed by the tangible objects within the ‘horse-racing’ context in an instinctively recognizable manner.

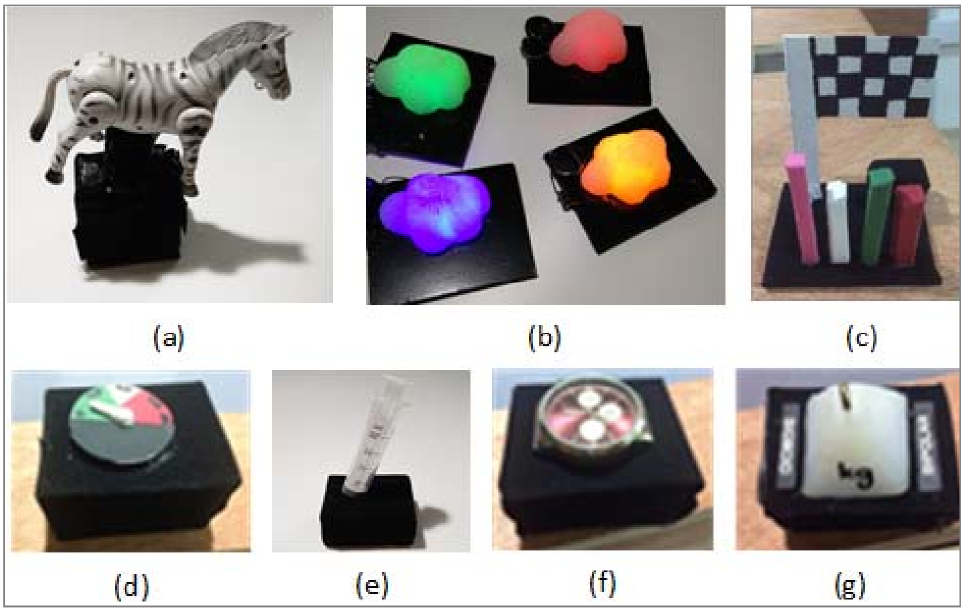


Figure 5.54 Active tangible objects contextualized for ANN operations including;
a) Horse - Context Simulator Controller, b) Clouds – Hidden Layer nodes,
c) Finish Podium – Output Visualisation, d) Speedometer – Input Speed Value,
e) Syringe – Input Health Value, f) Chronograph – Output Time Value,
g) Weight – Synapse Weight Adjustment

Through embedded interaction with digital and physical feedback, these devices provided the TUI framework with the ability to computationally couple physical manipulations with ANN operands. These interactions are further elucidated in the following systematical descriptions:

- Horse Simulator Controller – Figure 5.54(a): The horse tangible represents the contextual data scenario and consequently triggers the loading of the appropriate dataset on the neural network AI algorithm. Students dynamically use this tangible to alternate between setup and configuration modes of the designed ANN using positional shifting of the manipulative. Rotating the tangible at any stage in execution mode further controls and alters the training rate of the algorithm. This configuration interaction hence allows students to visualise and understand the training and convergence process in different modes of speed. The dynamic interaction is further communicated to the user via actively controlled feedback which via embedded actuators animates the figurines legs to simulate a functional galloping action whose pace is directly mapped with the ANN training rate.

- Cloud Nodes – Figure 5.54(b): A set of active cloud nodes were used to represent the abstruse nature of hidden layer nodes in ANN. Hence, by dynamically adding or removing these abstracted nodes, students were enabled to design and visualise the behavioural effects of differently configured topologies. The active tangibles were composed of translucent polylactide (PLA) material into which an actively controlled Light-Emitting-Diode (LED) was embedded. This intelligent interface aided student engagement by providing a colour-coded relational representation of output synapses. In addition, pervasive feedback interaction is used during the convergence process to intelligently engage student attention towards computational executions by timely triggered light strobes from the tangible.
- Result Podium – Figure 5.54(c): This finish line tangible embedded the representation of output results computed after each ANN iteration. By rotating the tangible, students can alter the result visualisation of either the tabulated output values or a graphical representation of the estimated percentage error fed back though each back-propagation epoch.
- Speedometer – Figure 5.54(d): This active input tangible was designed to represent the variable speed of the simulated racing-horse input data.

Via rotational interactions, students could alter the nodes input value which would be interactively reflected visually in both a displayed digital value as well as through proportionate dynamic analogue servo movement of the physical speedometer's hand.

- Syringe – Figure 5.54(e): The second input parameter was altered by users through the physical use of a syringe. This active tangible allowed students to alter the horse health data value which was exemplified as an input parameter to the ANN topology.
- Chronograph – Figure 5.54(f): This tangible output representation provided students the ability to toggle through testing or training simulation modes on the network. By actively engaging with the tangible through positional and rotational interactions, students can provide the ANN with an expected output data value, which would allow students to visualise the convergence process of the neural network to the newly trained outcome. Alternatively, the removal of this object indicated algorithmic testing conditions where the ANN needed to derive the output data.
- Weight Adjustment – Figure 5.54(g): This active TUI tangible was designed to allow students to experimentally learn and interact with the ANN operations. The translucent weight symbol allowed students to select and configure internal ANN synapses by tangibly engaging with their parameters. By dynamically altering the RGB light from an embedded LED, the TUI framework provided intelligent feedback to users by changing its internal color to match that of the linked synapse. This mitigated the potential graphical clutter of complex topologies by allowing the TUI framework to provide positional assurance to students on the intended selection. Rotational interaction during setup stage also allowed students to configure the synaptic activation function whilst during configuration mode, the interaction would override the synaptic weight value with users input. This data value was further actively related

back to students through a relational variation of lighting intensity of the physical tangible's LED.

5.8.2.2 *Digital User Interaction*

The proposed TUI framework embedded digital information through an interweaved GUI that provided an intuitive physical interactive experience. In stark contrast to the limitations imposed by Windows, Icons, Menus, Pointers (WIMP) systems, the proposed TUI architecture endowed additional flexibility options that were exploited to augment user immersion and learning processes.

The graphical interface was produced and implemented using Adobe Illustrator and the Unity^{TM} game development environment. The framework behavioural interaction was programmed using C# which allowed the integration of animations based on the tangible information obtained through the TUIO communication protocol (Kaltenbrunner *et al.*, 2005). Furthermore, the framework integrated with a developed Python neural network simulator which whilst providing authentic representation of real-time data through functional AI computation also unbounded students in their flexibility to customize and configurate ANNs.

The GUI interface pervasively aids student interaction by providing subtle visual cues which are designed to aid in the experimental learning process and digitally interlink with physical manipulation. The interweaved design elements between visual animations, TUI execution and user interaction of the proposed TUI framework are systematically detailed in this subsection through a review of the framework's operation sequence.

The start-up interface, illustrated in Figure 5.55(a), presents students with a sectional layout to aid in the stage design of the ANN. As shown within Figure 5.55, by suitably embedding visual iconic symbols, students are guided through the TUI interaction through projected cues. These aid to instinctively stimulate tangible interaction using appropriate placeholder indication. Once objects are placed on the interactive surface, the TUI framework makes use of digital timers, animated via radial filling as shown in Figure 5.55(c), to allow users to assert their decided actions through physical manipulations. Following the successful registration of user interactions, the framework progressively advances through execution/customization stages, providing students with the ability to personalize the pace at which they progress through their learning process.

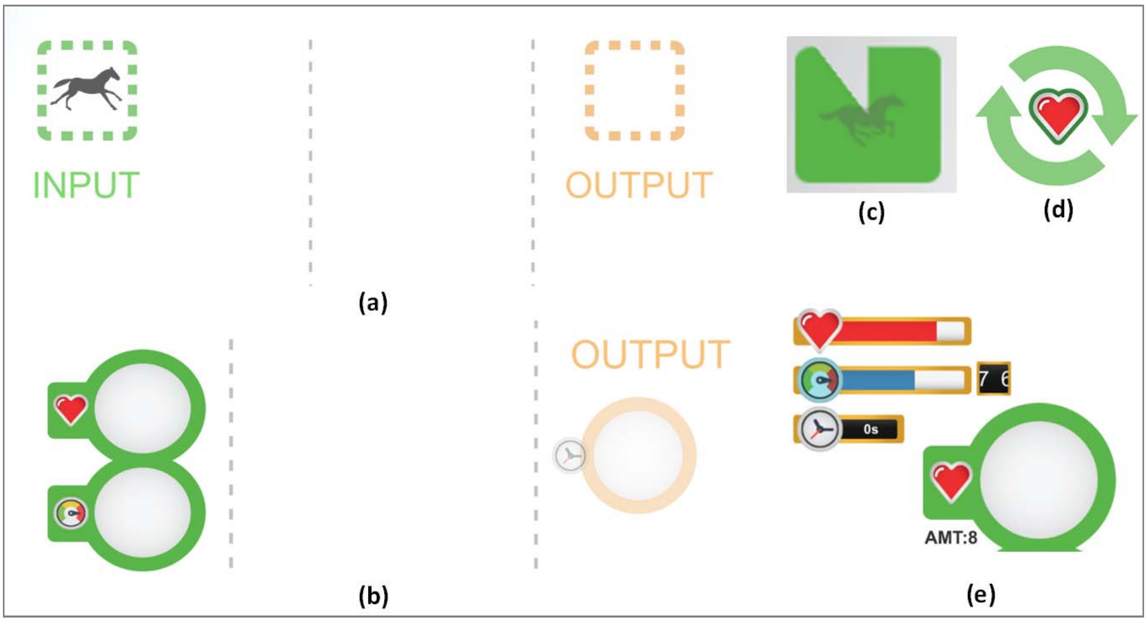


Figure 5.55 Digital elements designed for pervasive user interaction using the proposed TUI framework

Subsequent to the loading of the ‘horse-racing’ dataset, via the ‘horse’ scenario controller, the TUI framework presents the contextual network’s hyperparameters by visualising the distinct input and output nodes of the ANN as illustrated in Figure 5.55(b). Simultaneously, embedded LEDs actively flash on the respective input tangibles, pervasively diverting the student's attention towards the applicable interactive objects. Visual imagery complimented this smart interaction by helping students associate the digital/physical computational coupling by using indicative elements as pictured in Figure 5.55(d). By manipulating the appropriate tangible, students are able to customize the input/output parameters for health, speed and time values, thus experimentally designing and configuring their custom simulation. Interactive feedback is provided during this stage by blending the use of pertinent icons, completion bars, and variable value scrolls, as shown in Figure 5.55(e). This customization process is further reinforced within the TUI framework by the physical feedback provided using active actuators and input sensors on tangibles.

The use of proxemic interaction is also embedded within the tangible user interface by allowing students to dynamically configure synaptic links between nodes by placing the respective tangibles in physical proximity. This allows students to freely customize and experiment with ANN topologies augmenting the students' cognitive and learning process through user-centric progressive complex adaptions. To pervasively guide user's interaction, cloud tangibles which at setup stage represent the insertion of hidden nodes, are also interactively animated, by lighting up internally using the embedded LEDs as shown in Figure 5.56(a). Once utilized and connected, color-coded internal synaptic links are projected on these tangible 'hidden' nodes, representing their connected topology as illustrated in Figure 5.56(b).

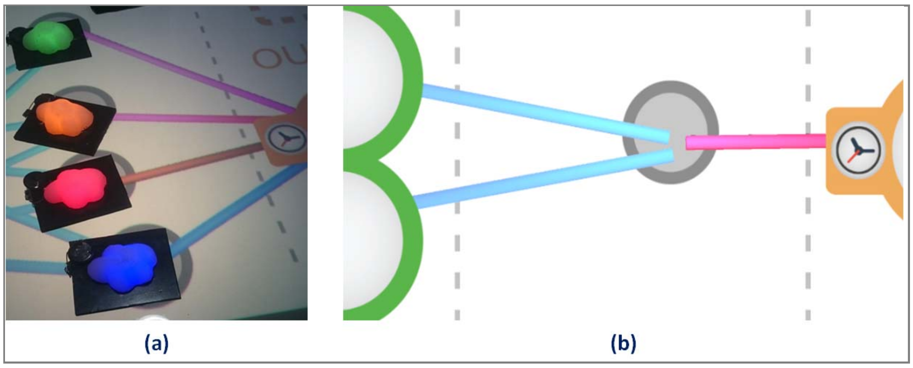


Figure 5.56 The configuration of hidden nodes and synapses using active cloud tangibles [7]

Following the connection of the ANN topology, the weight adjustment controller can optionally be utilized to customize the activation function on the synapse. This active tangible object is timely animated to indicate availability to the user. Thus, once placed near a created synaptic link, students can alter the selection

[7] Video clips of Multi-Threaded Scheduling TUI framework available on https://youtu.be/k23chasZu7o

of an algorithmic function. Making use of rotational interaction guided via pertinent circular graphics as illustrated in Figure 5.57, the framework provides students with the ability to experiment with different functional operands, which are visually explained to students using familiar mathematical graphs.

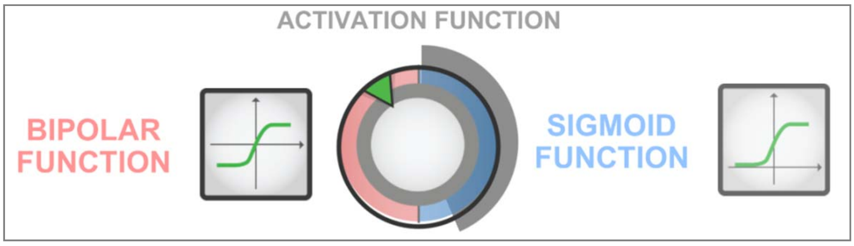


Figure 5.57 Selection of synapse activation function through rotational interaction with a dynamic digital timer to provide users feedback on their selected option.

Whilst the ANN is being constructed, students are provided with the option to switch between setup and configuration mode by visually projecting adjacent graphics near the horse simulator controller as shown in Figure 5.58(a). Once the tangible is positionally dragged onto the 'start' placeholder, the input graphical information is summarized for users as shown in Figure 5.58(b), whilst a new set of visual operands is projected near the tangible object. As shown in Figure 5.58(b), these rotational cues provide the user to set the ANN training rate, hence idling or speeding up the simulation as desired. In tandem with this interaction, the TUI framework actively governs the tangible controller to provide real-time interactive feedback by altering the actuated galloping motion of the horse in relational speed to the rotational digital selection.

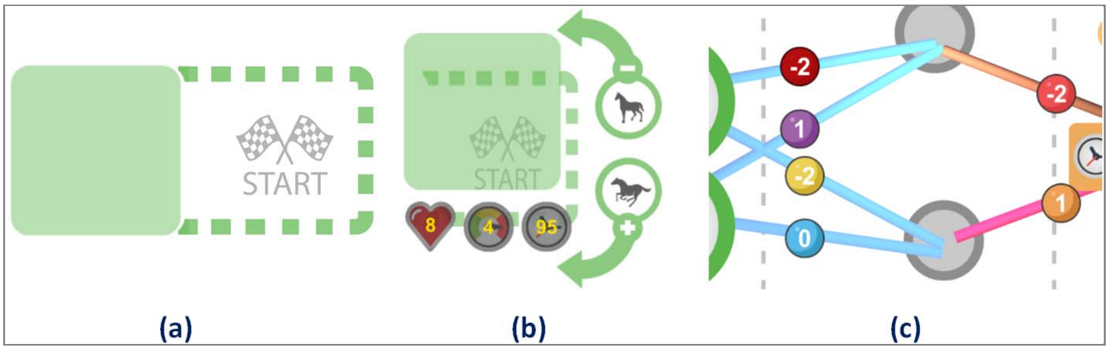


Figure 5.58 Visual digitization provided by the TUI framework in configuration mode.

At the start of the simulation in configuration mode, synapses are individually assigned random weights as common in most ANN implementations. This visual representation makes use of a suitably designed color-coding scheme, as shown in Figure 5.58(c), to facilitate the student's association of data. To further the experimental learning capabilities imparted by the TUI framework, the proposed implementation multiplexed the use of the 'weight adjustment' object to enable customization of the initial data in configuration mode. The active tangible is therefore illuminated in varying light colors whilst the framework transitions to configuration mode, providing a persuasive indication to users via the physical domain on its potential use. Once placed on the interactive surface, the weight tangible is digitally augmented with a dynamic color wheel, illustrated in Figure 5.59(a), which allows the user to accurately position and select individual synapses. Following the elapse of the interaction timer, the tangible object interactively changes light color to match the locked-in synoptic, indicating to the user the ability to configure specific data values on synapses via rotational interaction and digital visualisations as shown in Figure 5.59(b).

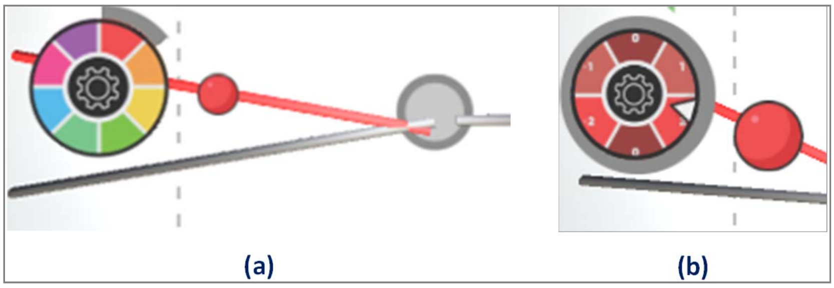


Figure 5.59 Tangible interaction allowing students to experimentally configure synaptic weight values.

Consequent to the interactive customization of values, the framework aids students understanding the conceptual operation and convergence process of ANN through animated visuals. As shown in Figure 5.60(a), data values are visualised traversing through nodes and synapses whilst appropriate animations are able to explain the mathematical value adjustments as signals propagate through the designed network. These dynamic visualisations provide a more intuitive understanding to the underlying concepts and procedural effects of the algorithm's iterations. Furthermore, at the end of each animated epoch the underlying ANN scripts compute and display the resultant values of the last few iterations in a tabular graphic projected adjacent to the podium tangible, as pictured in Figure 5.60(b). By physically altering this output tangible, students are further able to graphically interpret the convergence error computed through the last iterations, dynamically monitoring the effects of weight tuning on the algorithms backpropagation adjustment values and accuracy.

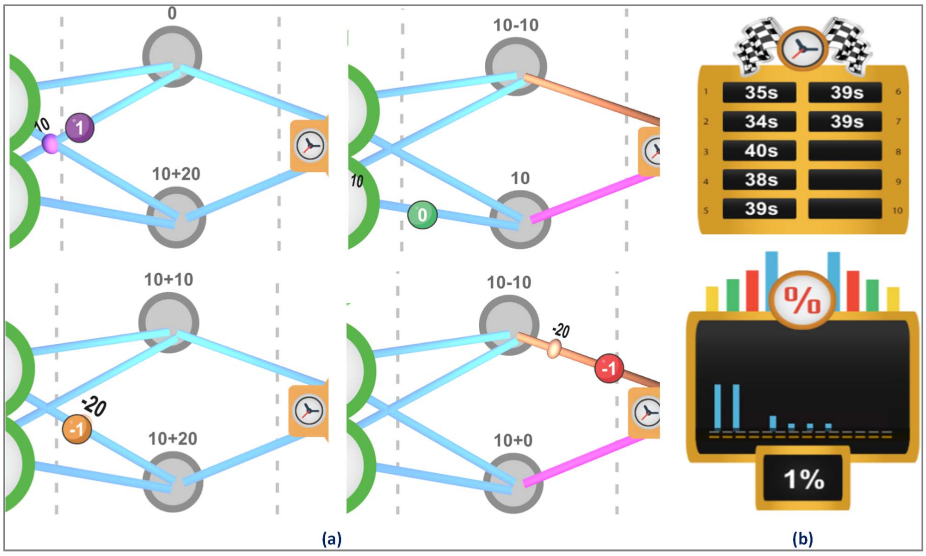


Figure 5.60 Digital visualisations highlighting internal computations:
a) Animated weight propagation and value calculation,
b) Output result times per iteration together with backpropagated error percentage for convergence.

Once the AI algorithm is sufficiently converged, students are able to further engage with the TUI framework to utilize and understand the developed ANN in predictive AI testing mode. In this mode of execution, the interweaved and perceptually coupled digital and physical domains, as pictured in Figure 9, enable students to self-evaluate the suitability and accurateness of their designed ANN topology by testing its validity on new input datasets. This allows students to individually self-assess their progress and uniquely customize the pace of their learning experience so as to obtain a deeper understanding of the AI concept.

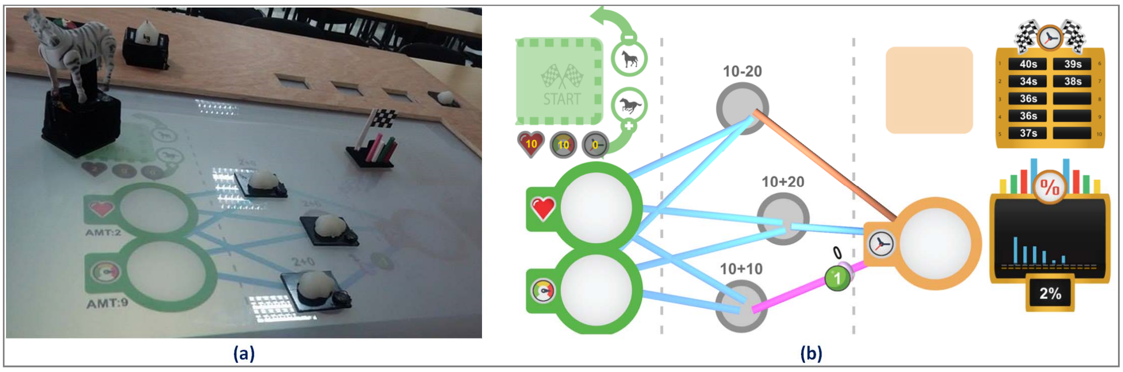


Figure 5.61 Perceptually and computationally coupled ANN model within; a) the physical domain, b) the digital domain.

5.8.3 Experimental Evaluation

The developed TUI framework was deployed for evaluation at Middlesex University Malta within undergraduate degrees in Computer Science and Information Technology. Purposive sampling was undertaken to select 32 students studying the module of Artificial Intelligence who voluntarily offered to participate in the evaluation study. This population sample size was deemed adequate in line with the guidelines in (Wilson Van Voorhis and Morgan, 2007). The undergraduate participants were either in their second or third year of study and varied in age between 18 and 24.

To evaluate the effectiveness of the proposed TUI framework, a direct comparison was undertaken against currently employed PC-based educational technology using a GUI educational simulator. To ensure no additional experimental variables are introduced in the evaluation, a similar GUI software was developed to that created on the TUI framework. As visualised in Figure 5.62, the educational software was optimized for GUI interaction and usability whilst retaining identical functionality and educational capabilities.

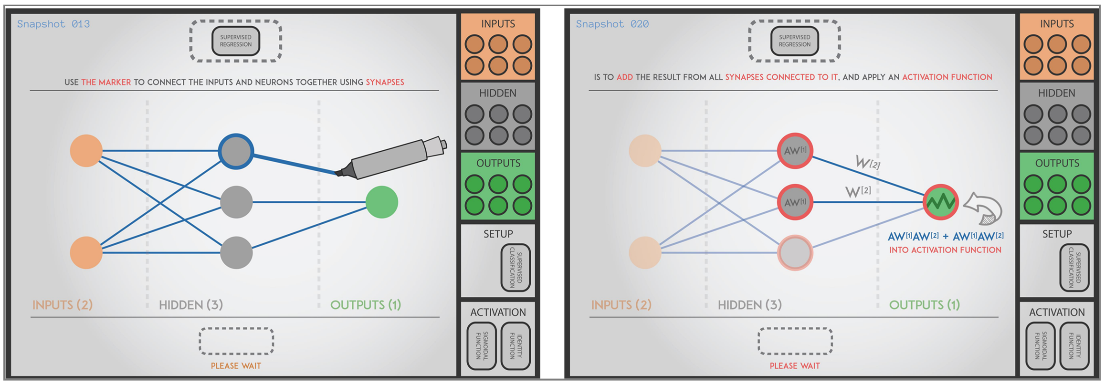


Figure 5.62 GUI software developed for comparative evaluation.

Artificial neural networks is a foundational topic within the selected course and commonly forms a threshold concept towards the student's progress and understanding of more complex algorithms. Hence, to maximize the evaluation potential of the proposed TUI framework, the experimental sessions were scheduled to coincide with the natural delivery of this topic within the curriculum.

5.8.3.1 Evaluation Methodology

An evaluation methodology was implemented which was designed to yield a quantitative analysis of the effectiveness and suitability of the proposed TUI framework in HEI contexts. This evaluation data was obtained by using both a usability questionnaire and an open-ended assessment where questions covered both theoretical as well as practical design aspects of ANN concepts. Figure 5.63 outlines the sequential flow of student evaluation, lecturing and assessment sessions;

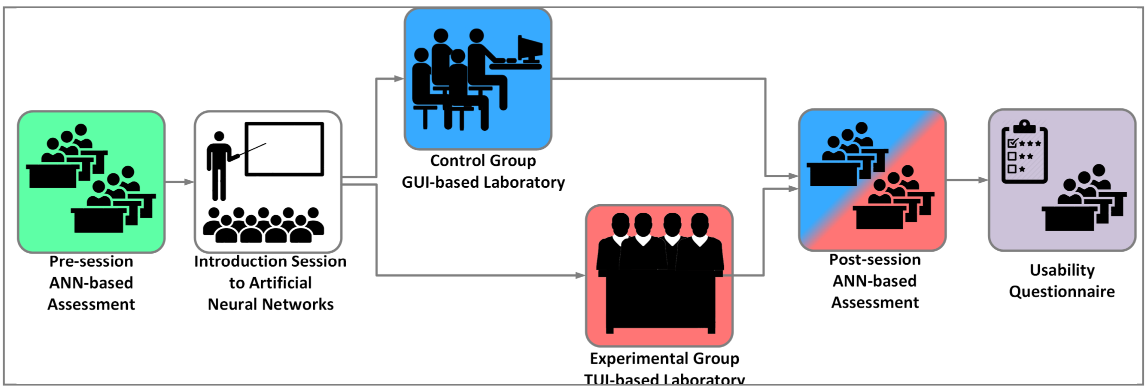


Figure 5.63 Evaluation stages for assessing the suitability of educational technologies for ANN concepts.

To mitigate the potential bias introduced by the students' a priori knowledge of ANN potentially acquired from their related work experience and varied demographics, a differential evaluation methodology was adopted to provide summative assessment on the level of knowledge gain obtained by students (Catala *et al.*, 2011; Skulmowski and Rey, 2017). To this end, upon commencement, all students were provided with a timed pre-session assessment on ANN knowledge. This examination was composed of 12 open-ended questions, as shown in Appendix B.7.1, and covered various aspects of detail and conceptual understanding of the ANN concept. The results obtained from this assessment provided an individualistic knowledge baseline for each student prior to being provided formal tuition on ANN.

Following this initial assessment, students collectively attended a short introductory session. This was delivered in traditional lecture format, whereby basic terminology and foundation principles for neural networks were introduced. This session was delivered by the usual lecturer using the standard lecture slides conventionally adopted for the module to ensure a consistent and appropriate explanation is provided. Subsequent to the lecture delivery, students were randomly split in two equal groups for their laboratory/seminar session on the topic. These cohorts composed the experimental and control groups respectively for the evaluation methodology described and where instructed consecutively as illustrated in Figure 5.63. During the laboratory sessions, students sub-grouped in sets of four (4) to solve a number of given group work tasks. The latter were identical to both cohorts and involved the experimental design, construction and analysis of different ANNs topologies within a 'horse-racing' contextual example. The designed variable within the experiment was to enable students within different groups to utilize a different educational technology to undertake and solve the laboratory tasks. Thus, whilst the control group students adopted the traditional GUI-based educational software shown in Figure 5.62, the experimental group students were able to interact with the proposed TUI adaption pictured in Figure 5.61.

Following the successful completion of their respective tasks, all students were provided with a usability questionnaire for the respective educational technology utilized as well as a second assessment using similar open-ended questions on ANN concepts. The questions in this examination were designed to assess the various aspects of conceptual understanding including theoretical, detail-focused, procedural and problem-based knowledge as detailed in Appendix B.7.2. These quantitative assessments were designed to provide an evaluation on the knowledge gain obtained by each individual student during the respectively attended session. Equitable analysis on the assessment grades together with the quantified subjective evaluation provided by students in relation to the interactivity and usability of the designed educational technology were able to aid evaluate the respective aptness and efficacy of the proposed TUI framework in HEI contexts.

5.8.3.2 Results and Discussion

The grades obtained by students within each of the assessment sessions are visually presented in Figure 5.64. The figure provides a comparative evaluation of the results obtained by students in each distinct question during their pre-session assessment (green) as well as their subsequent post-session assessment following interaction with a GUI-based or TUI-based laboratory session (red or blue respectively). This data was evaluated for each individual student in both educational cohorts using a paired-sample t-test.

Results outlined that students undertaking the control laboratory improved their mark to 39.1% (σ: 15.6) from their initial pre-test score of 15.4% (σ: 3.1). On the other hand, students who engaged with the proposed TUI framework during the experimental setup achieved a post-test average grade of 71.2% (σ: 14.4). Thus, in contrast to the 23.7% (σ: 16.4) knowledge gain obtained during the GUI-based computer laboratory sessions, the proposed TUI framework provided students with a knowledge gain of 55.8% (σ: 13.7) at $\rho < 0.001$ as shown in the overall comparison in Figure 13. Analysed under an independent samples t-test, the proposed TUI framework resulted in a knowledge acquiring difference of 32% (σ: 6.1) at $\rho < 0.001$ with respect to the control student cohort.

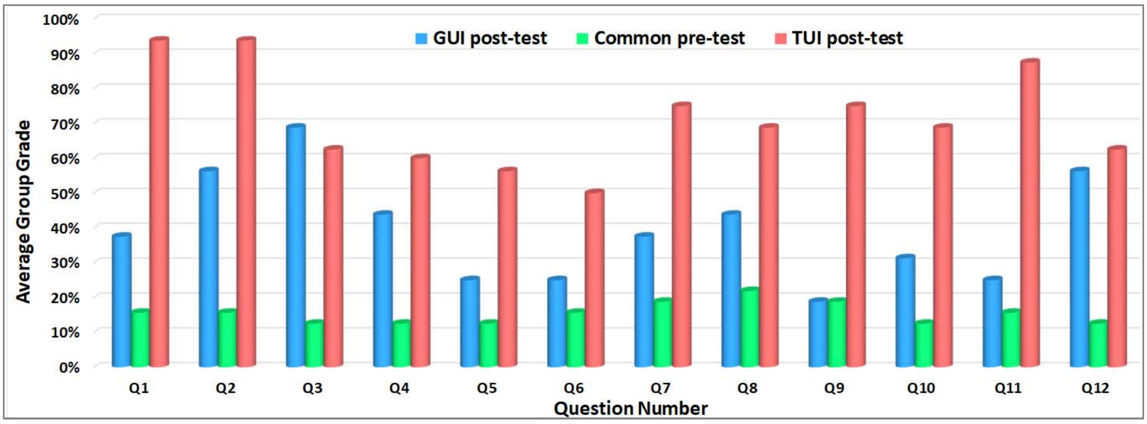


Figure 5.64 Average grade obtained for each assessed question during the: (left) Post-test of GUI control group, (centre) Pre-test undertaken by all students prior to formal tuition on ANN, (right) experimental group after using the proposed TUI framework.

This difference was directly attributed to the effectiveness of the proposed tangible interactive framework to engage students with abstracted ANN operational concepts. This was achieved in stark contrast to the experimental control group which by adopting a feature-identical GUI setup, illustrated the limited capabilities of the educational technologies adopted conventionally in HEIs.

The remarkable achievements obtained through the TUI interaction were further analysed to obtain a deeper insight into the teaching and learning capabilities delivered by the framework. The nature of the open-ended questions delivered within assessments were thus segmented according to the different aspects of knowledge evaluated, as shown in Figure 5.65.

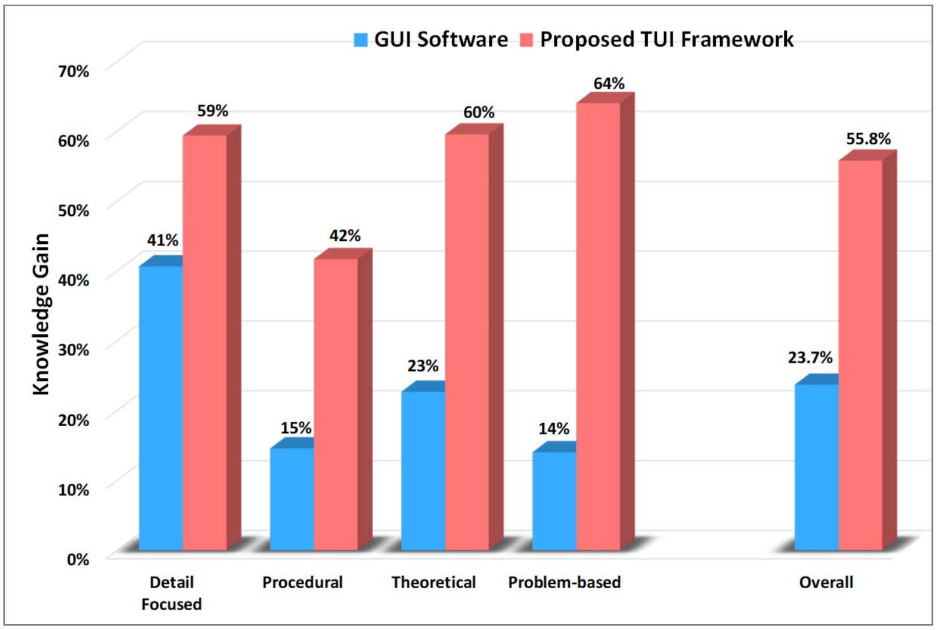


Figure 5.65 Knowledge gain analyses between educational technologies at ρ < 0.001 statistical significance.

The classified results show that both technologies performed with equitable effectives on ‘detail oriented’ aspects of knowledge with Q3 in Figure 5.64 showing a marginal increased ability by GUI software to aid in teaching and learning theoretical definitions. Conversely however, results in Figure 5.65 immediately highlight the ability of the proposed TUI framework to aid students understand the procedural and theoretical aspects of ANN concepts deeper than that provided by similar GUI software. This can be attributed to the students’ ability to tangibly interact with the system’s active functionality using instinctive manipulations and feedback channels that augment focus and understanding of the conceptual representations. Furthermore, as outlined by performance difference in answering problem-based questions, the intrinsic capability of the proposed TUI framework to contextualize ANN operation within a familiar environment by using adequately designed tangible representations aids students to assimilate knowledge, thus heightening their ability to apply and understand the underlying abstracted concepts in problem-oriented scenarios.

The aptness of the proposed TUI framework for adoption in HEI was also evaluated using a usability questionnaire that was provided to both groups of students after interacting with their respective educational technology. Using a bi-polar five-level Likert scale, chosen as a suitable reference scale to provide reliability in comparative subjective assessments (Ahmad and Ahlan, 2015), students were asked to quantify their experience in various aspects of their educational pursuit as shown in Appendix B.7.2. The aggregated results are presented in Figure 5.66.

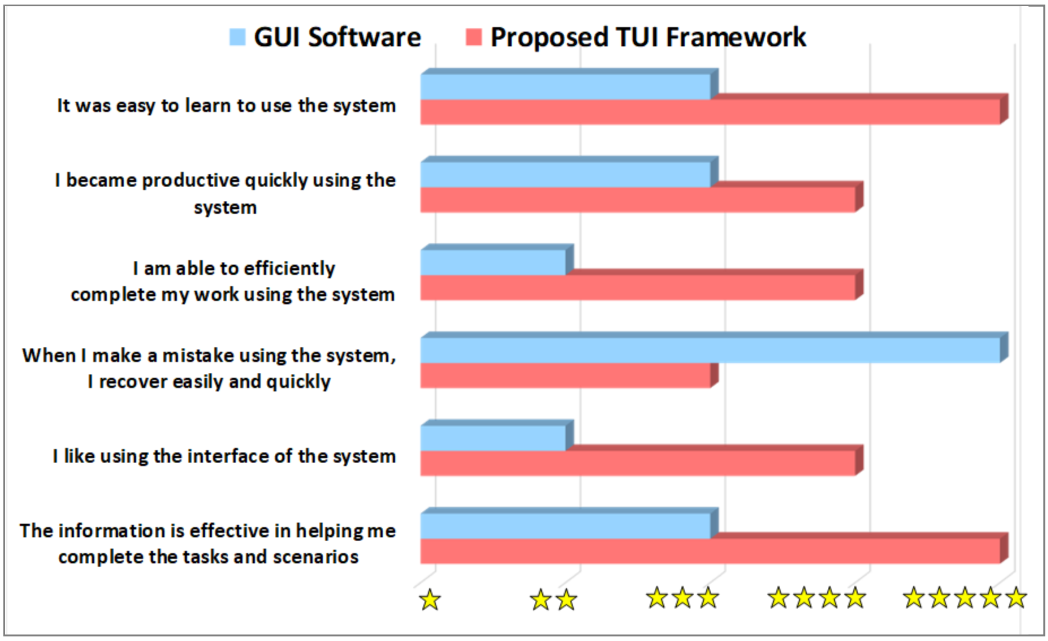


Figure 5.66 Usability results for both educational technologies.

The subjective usability results outline the effectiveness of the appropriately designed TUI framework to be interacted by users in an intuitive, productive, and ultimately enjoyable manner. Student's feedback demonstrated that albeit the GUI and TUI systems used projected the same information, the information in the TUI framework was perceived to be more effective in understanding and completing the intended ANN tasks.

As shown in Figure 5.66, a limiting usability factor was conversely noted in the easiness for users to recover the ANN to earlier versions, which when compared to ‘back button’ deployments in GUI software, the proposed TUI framework necessitated users to redefine parameters and connections by manipulating tangibles accordingly. Nevertheless, questions relating to efficiency in achieving the intended outcome illustrate that students still felt more productive when operating a TUI interface in developing and analysing different ANN configurations.

A combined interpretation of results corroborates on the effectiveness of the proposed TUI architecture to interlace the digital information within the tangible domain through a more immersive interface using the novel active tangible interaction paradigm. This reflected on the framework’s heightened ability to engage multiple students together whilst facilitate the collaborative learning and engagement on contextual problem-solving scenarios.

5.9 Robot Operating System

The search of alternative pedagogies for teaching and learning technical concepts within the dynamic domain of computational science and technology steadily sought the adoption of evermore engaging educational methodologies (Mosley and Kline, 2006; Dyne and Fjermestad, 2012; Eguchi, 2014). The inclusion of robotics within curricula presents intriguing learning gains based on the ability of the topic to enthral students' problem-solving and thinking skills (Benitti, 2012; Atmatzidou and Demetriadis, 2015). The peculiar nature of robotics education interweaves computer hardware and software integration, providing a combined insight into cross-discipline knowledge domains such as; mechanical, electrical, electronic and software engineering (Armitage, 2001; Hernandez-Barrera, 2014). Apart from engaging the simultaneous use of creativity and technical skills, the combined knowledge skillset required in the domain intrinsically presents an opportune instance for the development of communication and collaborative skills (Andruseac and Iacob, 2013; Cubero, 2015). The complexity in amalgamating these skillsets when teaching and learning advanced robotic concepts within HEIs, however, poses several difficulties for educators, leading academics to seek abetment from education technologies within their delivery (Armitage, 2001; Norton, McRobbie and Ginns, 2007; Benitti, 2012).

5.9.1 Educational Technology for Robotics

The integration of educational technologies within robotic concepts has long been sought after for its innate ability to interactively engaging students within education and freeing the way in which instructors and students interact (Astatke *et al.*, 2016). The adoption of technology aids to bridge the gap between narration and simulation of robotic concepts, enhancing and augmenting students' learning experience (Giuseppe and Martina, 2012). This has been achieved in past literature by providing students with the ability to visualise their operational concepts using web-based simulator tools such as algorithmic flowcharts (Norton, McRobbie and Ginns, 2007) and digital logic circuits (Kuc, Jackson and Kuc, 2004) to aid in the design of robotic elements whilst simplifying other development aspects. The use of Graphical User Interface (GUI) simulators facilitates the familiarization with complex concepts such as those experienced in embedded microcontroller programming, hence allowing novice students to engage and progress further in understanding the subject (Sirowy *et al.*, 2009).

Nevertheless, the use of GUI simulators for educating robotic concepts has been critiqued for its inability to engage students and provide effective opportunities for skill development and deep learning that can alternatively be obtained whilst problem-solving tangible aspects of robotic design and programming (Weiss, Gridling and Proske, 2005). Furthermore, Mitnik *et al*. (Mitnik, Nussbaum and Soto, 2008) argue that most GUI tools employed in robotic education lack direct focus on the teaching of intrinsic concepts of robotic architectures, but rather focus on supporting closely related topics such as mechatronics and computer programming. In addition, GUI architectures impose an uncoupling of action and perception in Human Robotic Interactions (HRI), thus reducing the intuitiveness and concentration ability of engaged students (Fiorentino, Monno and E., 2010).

Consequently, Tangible User Interface (TUI) has garnered increased interest as an educational technology which is capable to mitigate these limitations whilst naturally interweaving the physical and digital domains (Fernando, Dupre and Skates, 2016). By going beyond traditional computer peripherals, TUI architectures allow users to interact with digital information through manipulation of everyday physical objects and triggered behaviours (Ishii, 2008b). This technology resonates with robotics education by encouraging collaborative and playful learning (Marshall, Rogers and Hornecker, 2007), whilst inherently embracing students using multisensory perception channels including; vision, auditory and touch (Zuckerman, Arida and Resnick, 2005). Furthermore, the experimental nature of TUI setups provide students with an interactive opportunity to develop a constructive understanding of underlying concepts by actively engaging with their learning process (Lucignano *et al.*, 2014).

The use of constructive assembly TUI architectures have enabled educators to introduce children to robotic concepts normally considered beyond their abilities (Shaer and Hornecker, 2009), by providing educational setups that allowed students to connect and configure programmable LEGO™ blocks sequentially (Sapounidis and Demetriadis, 2013). Similar laboratory robotic kits were also successfully employed by (Weiss, Gridling and Proske, 2005) and (Cubero, 2015), whereby children that designed and created robotic artefacts via collaborative interaction, obtained a deeper and more hands-on understanding of the taught subject (Ceccarelli, 2003). These results concur with the observations of (Strawhacker, Sullivan and Bers, 2013) on playschool children, whereby the use of TUI systems delivered logic and programming concepts more effectively than conventional GUI educational technologies.

Whilst the experience of integrating learning in an attractive, fun and interactive manner provided positive results for children, the above TUI systems fail to scale with equal effectiveness when utilized with adult higher-education users. The need to deliver more abstract and complex engineering concepts further requires TUI architects to provide more advanced manipulations as well as the ability to visualise detailed information.

5.9.2 ROS TUI Framework

The proposal within this section aims to address the necessities and limitations outlined in literature by proposing a novel TUI framework for teaching and learning advanced robotic concepts. Moreover, this research makes its contribution by analysing the suitability and effectiveness of TUI systems to educate undergraduate students in conceptual theory and practical knowledge when designing and developing a distributed Robot Operating System (ROS) architecture (Quigley *et al.*, 2009) for data fusion within an Internet of Things (IoT) infrastructure.

The proposed framework incorporates the TUI architecture designed in chapter 4 with the novel introduction of active tangible objects within the field of tabletop TUI architectures. Tangible objects were mounted to a 3D printed cylindrical base, underneath which 'amoeba' reacTIVision markers (Kaltenbrunner and Bencina, 2007a) were attached as shown in Figure 5.67(b). The unique rotation-variant fiducial patterns on these markers allow the framework to discriminate and identify each object from the captured video stream, whilst tracking their respective physical position and orientation. The 7.4cm wide by 4cm high cylindrical base, illustrated in Figure 5.67(a) was carefully designed to promote the ergonomic use of rotation on tangibles, providing the user with an instinctive interaction option.

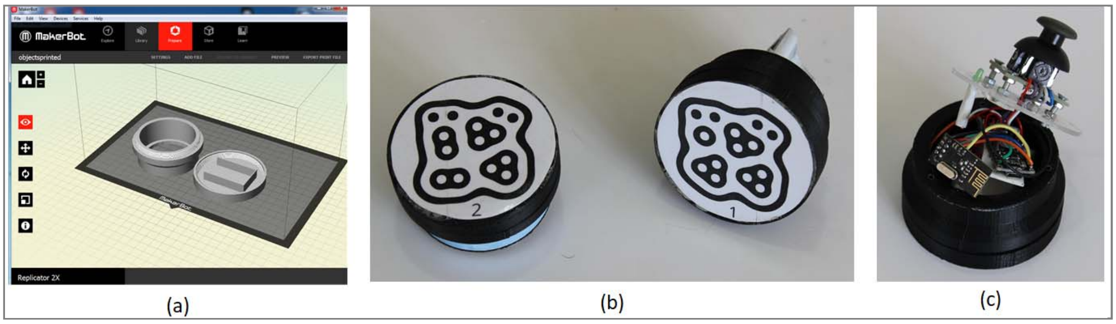


Figure 5.67: Design of Active TUI base unit showing:

(a) 3D Printed hollow base in cylindrical ergonomic dimensions,

(b) reacTIVision 'amoeba' fiducials attached underneath (Kaltenbrunner and Bencina, 2007a),

(c) TUI base unit with active processing components.

The active tangible concept was achieved by making use of autonomous computational units that are able to wirelessly communicate with the processing server. Hence, as pictured in Figure 5.67(c), each base unit embedded within an Arduino Nano^{TM} microcontroller chip together with a battery, a communication module, LED status lights and a vibrator motor. The latter components provided an additional layer of interaction, whereby the proposed TUI framework provided feedback by either altering the LED light colour or via haptic vibration during tactile interaction. Using a 2.4Ghz RF transceiver, information could be independently transmitted and received from the server processor via a serial communication protocol, enabling the framework to provide real-time input interaction and feedback visualisation.

The design and selection of intuitive and familiar tangible objects provide a foundational advantage for TUI systems which can support students to associate a priori knowledge and functionality to the TUI models. To this end, commonplace robotic network components deployed in microprocessor-based ROS architectures were utilized to represent computational nodes and sensor modules as shown in Figure 5.68(a) and Figure 5.68(b) respectively.

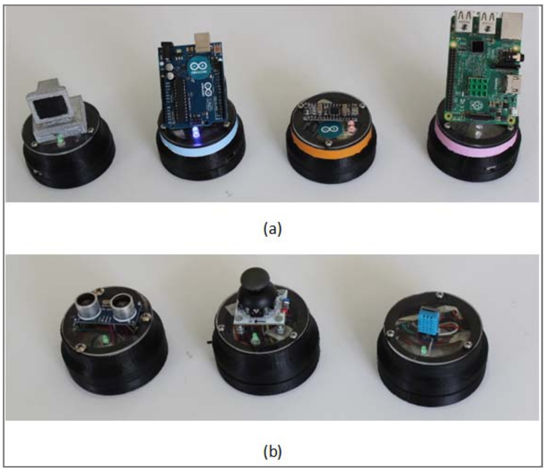


Figure 5.68: Design of Active TUI robotic manipulatives;

(a) ROS-based microprocessor nodes (incl. Master PC, Arduino Uno, Arduino Nano and Raspberry PI),

(b) Robotic sensor modules (incl. Ultrasonic distance, joystick controller, temperature/humidity),

These components provide students with the ability to configure and design a ROS-based smart sensor architecture employ a variety of microprocessor nodes such as Ardunio™ and Raspberry Pi™. Moreover, the active nature of the designed tangible objects affords yet another interaction domain to the proposed TUI framework by allowing the real-time data input following users' interaction with the sensed environment. To this end, a range of sensor modules including; an ultrasonic distance sensor, a temperature/humidity sensor and a dual-axis joystick controller were electronically connected to the base units, which enabled the transmission of captured sensed information to the TUI processing server.

5.9.3 Tangible Interaction

The digital augmentation of these physical models is primarily obtained via the perceptually and computationally coupled projection of visual information on the tabletop interactive surface. The graphical software was developed in C# on the Unity^{TM} game engine environment with the integration of the reacTIVision framework established via the TUIO library and protocol (Kaltenbrunner *et al.*, 2005). The proposed framework allowed the embodiment of physical objects with digital information by spatially multiplexing output data in the perceptual proximity of the tangible manipulatives. Spatial freedom was provided by the developed software which allowed the unbounded placement of artefacts to enable users to experimentally construct different ROS enabled IoT architectures and topologies. Furthermore, digital feedback considerations were embedded within the software architecture to indicate progress and pervasively guide users in understanding the underlying ROS operational concepts. Visualisation of abstract and dynamically complex information relating to network component is coupled by displaying of information structures adjacent to tangible objects.

As shown in Figure 5.69(a), the internal topological table contained and updated within the master node controller of a ROS architecture is visualised to students and enables facilitated understanding by means of colour coding and structured graphics. This allows users to understand imminently the current state of the topology as well as the mode of operation of individual node elements. Furthermore, this information is computationally coupled with the tangible object and is made available to users only on utilization and system detection of the assigned ROS master controller.

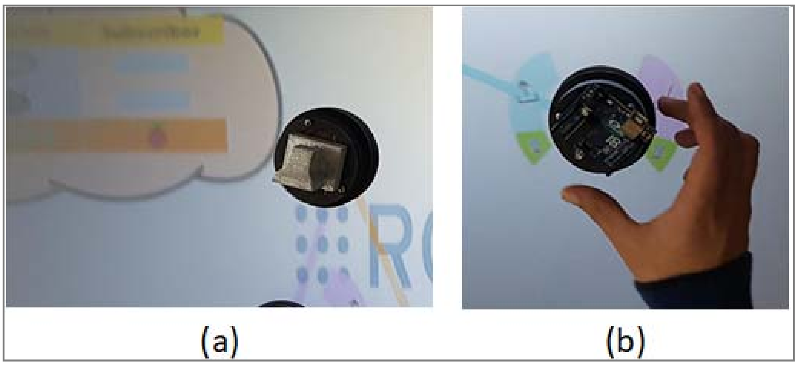


Figure 5.69: Perceptually and computationally coupled digital feedback projection:
a) Visualisation of abstracted information on objects,
b) Embodiment of rotational information menu.

Each IoT microcontroller node is augmented digitally by visualisation of a configuration selection wheel, illustrated in Figure 5.69(b). This visualisation prompts the user to instinctively interact by rotating a digital pointer and consequently assign and alter the mode of the node set into either publishing or subscription mode for available data transmission topics. Once a node becomes active within the topology, this triggers link visualisations between the node and the master controller, which students apprehend via colour-coded registration links, shown in Figure 5.71(a), as well as vibration and LED light feedback.

The detection of sensor modules triggers different animations which relate to the state of the data sensor and its connection status. As visualised in Figure 5.70(a), a data loss animation characterizes unconnected sensors together with a directional arrow suggesting to the student the direction of the closest node. Once the sensor is physically shifted to within the proximity range of a microcontroller node, the user is provided positive feedback via the light blinking of an in-built status LED together with a haptic vibration pattern to signify a successful sensor unit connection. As pictured in Figure 5.70(b), the visual projections are also triggered, and a serial data transmission animation is displayed emanating from the sensor. Moreover, a graphical symbol animation sequence illustrated in Figure 5.70(c) interactively updates itself to reflect the user input value, measured by the active sensor, by altering graphical aspects in the thermometer colour or measuring tap distance.

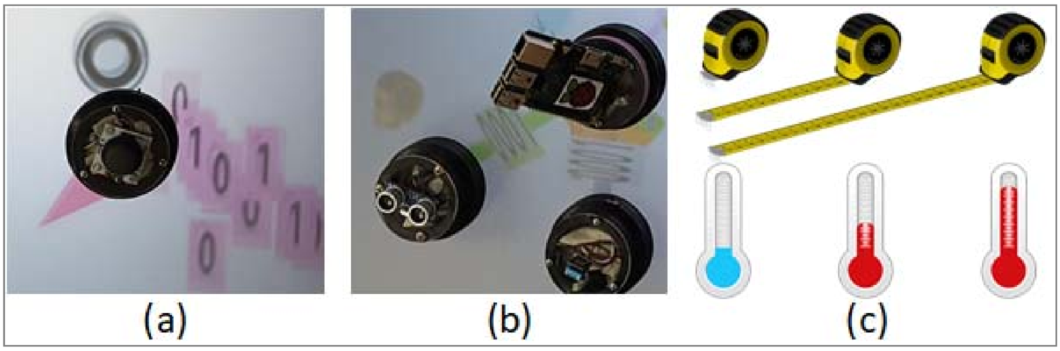


Figure 5.70 Sensor module status and visual feedback [8]:

a) Unconnected sensor with data loss and directional guidance for link establishment,

b) Active sensor transmitting binary data to a node,

c) Animated imagery providing real-time measurement feedback from active sensor data.

Within the ROS architecture, once an active IoT node is receiving data from sensors, this can be configured to publishing mode, whereby a data topic gets broadcasted with the acquired real-time sensor measurement data. The proposed framework aids the understanding of abstracted processes such as node data-fusion by providing animated illustrations of data transmission between distributed nodes. This occurs for every active node unit that is configured to subscribe to the same data topic. As shown in Figure 5.71(b) a visualisation is triggered that illustrates data packets flowing through topic links and subsequent information fusion occurring at the node prior to retransmission. Thus, the topologies in Figure 5.71 illustrate the physical and digital integration provided by the proposed TUI framework which allows students to collaboratively configure and experiment with ROS-based IoT architectures whilst interactively understanding the underlying conceptual functionality.

[8] Video clips of Robotic Operating System TUI framework available on https://youtu.be/Nl-JkFmtB8A

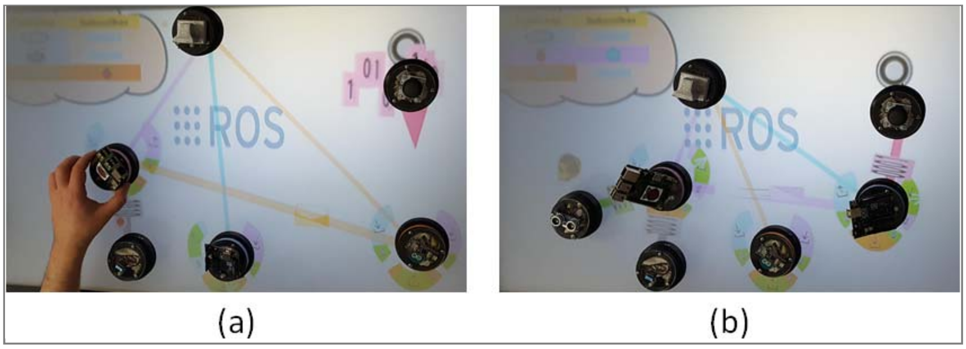


Figure 5.71 ROS-based IoT architectures communicating data.

5.9.4 Evaluation

The proposed TUI framework in sections 5.8.3 and 5.8.4 was evaluated via deployment within an undergraduate programme at Middlesex University Malta. 33 students reading a degree in Computer Science (Systems Engineering) were selected for the study based on their enrolment within a 'Systems Engineering for Robotics' module. The introduction to Robot Operating System (ROS) concepts form a threshold concept within the progress of this module and impacts significantly on the student's capabilities of achieving the intended learning outcomes. To this end, the evaluation session was coordinated as to coincide with the appropriately scheduled lecture delivery within the module.

5.9.4.1 Evaluation Methodology

An evaluation methodology was implemented which was designed to yield a quantitative as well as observational analysis of the effectiveness of the proposed TUI framework. The former data was obtained by preparing assessment questions which covered both theoretical as well as practical design aspects of ROS architecture development. Observational information was acquired by developing a check sheet list of behavioural cues which would be noted during educational sessions. Figure 5.72 outlines the sequential flow of student evaluation stages and split groups.

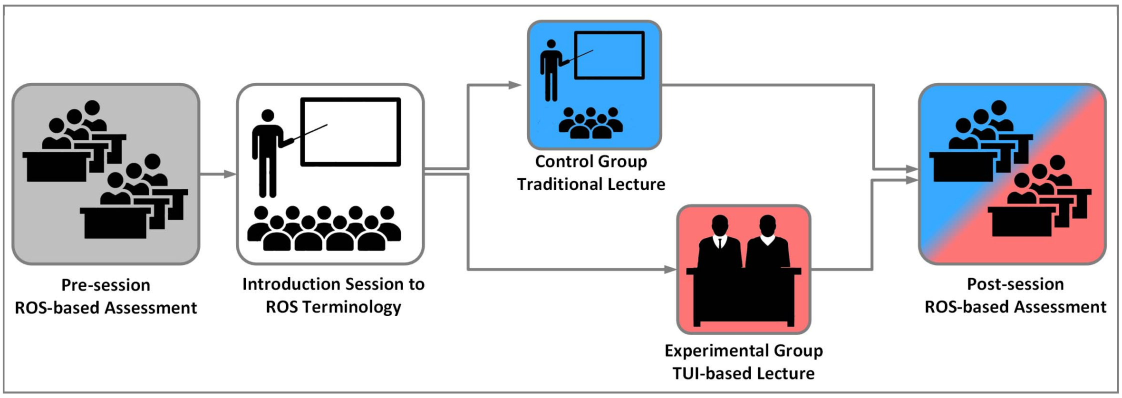


Figure 5.72: Evaluation stages designed for implementation within an HEI context.

To remove potential bias from student's a priori knowledge and exposure to advanced robotics concepts, all students were provided with a timed pre-assessment of ROS knowledge. A series of seven (7) questions were provided which covered a combination of theoretical knowledge, detail understanding as well as problem-based topology design outlined in Appendix B.8. The results from this examination provided an individualistic knowledge baseline for each student prior to formally undertaking lecturing tuition.

Subsequently, as shown in Figure 5.72, students attended together a short introductory session. This was delivered in conventional lecture format, whereby basic terminology and foundation principles were introduced. Following this session, the students were randomly split into two quasi-equal groups which composed the control and experimental groups respectively. The control session was designed to cover the explanation of ROS concepts using traditional educational technology making use of a smartboard, digital projection, and whiteboard fixtures. Following a lecturing session, students were provided with a case-based example on which they collaborated in pairs to solve the example problem on an active smartboard. On the other hand, the experimental group collectively attended a session covering the same content yet explained using the proposed TUI framework. Similarly, to the control group, students were provided with the same case-based example problem, which they were encouraged to collaboratively solve by interacting on the TUI architecture in pairs. To reduce the potential of experimental bias, both sessions were timed to be of equal duration, observed using identical criteria, delivered by the same lecturer successively, and used the same topic slides. At the end of each session, students were once more assessed with a different assessment that again covered the same conceptual and practical knowledge of ROS principles.

5.9.4.2 Analysis of Results

Analysing the combined pre-test scores from both groups in a means independent-sample t-test, highlights that no statistical difference or bias was present between the a priori knowledge of students ($\rho > 0.798$). This validates the randomness of the group split which shows that no statistically significant bias was present in the average technical knowledge between student groups prior to the lecturing session.

Making use of unique student IDs, the obtained results from post-tests scripts were compared on an individual basis to the pre-test score for each separate student. These were subsequently analysed using a paired-sample t-test. Thus, as illustrated in Figure 5.73(a), the control group, who initially held an average score of 41.1% (σ: 21.7), improved their average understanding to a post-test mean score of 69.4% (σ: 12.62) after the traditional lecturing session. Whilst the effectiveness of using traditional educational technology to teach and learn ROS concepts was evidenced in this cohort, even more, significant improvements were noted within the TUI experimental group. The latter, who initially held a similar level of knowledge about the subject (pre-test mean difference of 39.8%, σ: 17.1), increased their understanding by 42.9% (σ: 9.0), thus registering an average post-test score of 82.3% (σ: 7.9). This substantial knowledge gain was further confirmed using an independent-sample t-test on both populations which, as shown in Figure 5.73(b) confirmed at a 95% confidence interval ($\rho < 0.05$) that the proposed TUI framework yielded a net increase in ROS understanding by 14.6% (σ: 6.9) amongst the different lectured class groups.

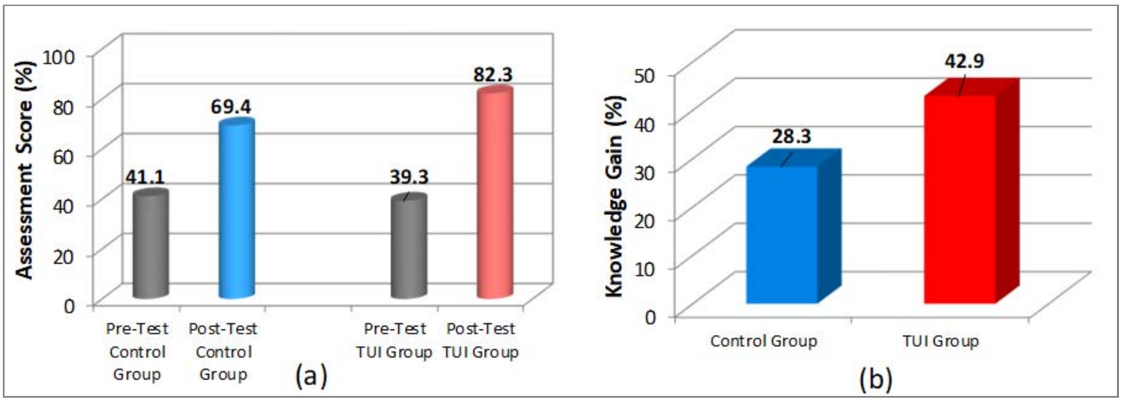


Figure 5.73: Evaluation results from both groups indicating:

a) Average score improvement in assessment,

b) Average knowledge gain from both pedagogies.

A component-based analysis from the post-test questions, shown in Appendix B.8.1, outlines four distinct types of knowledge assessment that were addressed in the evaluation. The effectiveness of the experimental and control educational technologies to teach and learn the different types of ROS conceptualisation knowledge are distinctly represented in Figure 5.74. Whilst a general improvement is noted across all aspects for TUI lectured students, statistically significant ($\rho < 0.01$) knowledge gains between groups were registered in favour of TUI implementation of procedural (mean difference: 21.1%, σ: 7.9) and problem-based concepts (mean difference: 15.1%, σ: 3.9). The latter result, assessed on a case-based problem-solving question to design an IoT architecture in pairs, further affirms the collaborative learning capabilities that are experienced by students whilst learning through TUI systems.

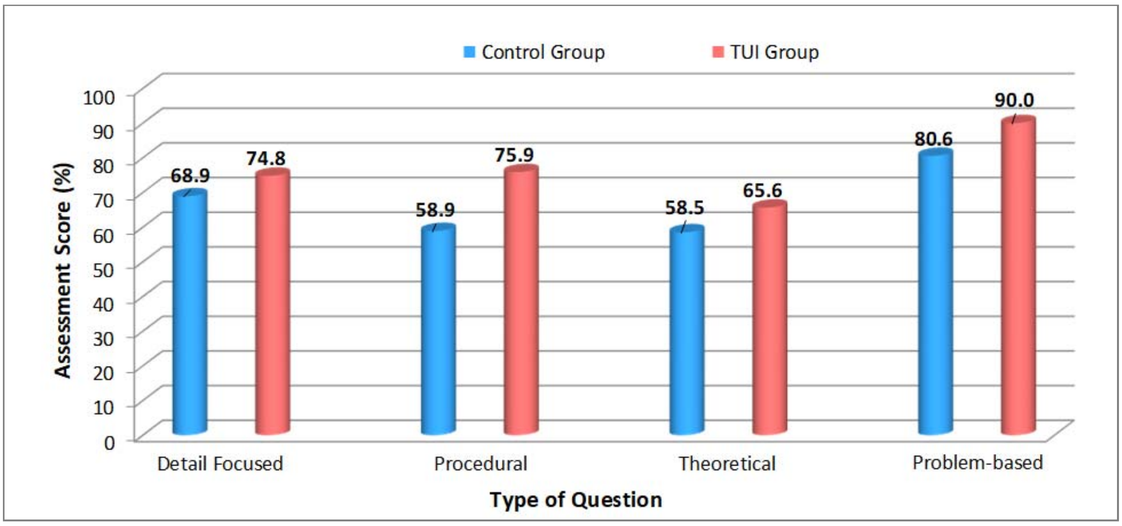


Figure 5.74: Comparative performance analysis on type of knowledge evaluated.

Furthermore, the behavioural analysis was undertaken on both lecturing sessions was quantified using an observational check-sheet. The analysed results outline substantial differences in the level of engagement amongst students in different lecturing groups. In contrast to the traditional lecturing approach, TUI students were less easily distracted with personal devices and showed higher interest in interacting with the lecturing session. The latter was observed in both a heightened amount of investigative questions during delivery as well as significantly higher collaborative interaction between pairs of student whilst solving an IoT architectural oriented problem-based question. Positive behavioural observations were also instinctively noted from the lecturer, which whilst delivering the ROS session could make use of a much more intuitive and efficient educational technology for aiding explanation and conceptualization.

5.10 Synopsis

The different sections of this chapter described unique TUI frameworks adapted towards teaching and learning a variety of threshold concepts commonly encountered in computational science and technology education. Collectively the diversity of domains investigated, and the distinct nature of each abstracted concept ensured that no bias was presented from unique constructs of highly complex and abstract notions. Most TUI frameworks adapt concepts within contextual examples through the interwoven design of tangible interaction elements that provide students with a facilitated approach to understanding the abstracted notions being represented. A plethora of interactive techniques are investigated in each unique design, with TUI frameworks for *Networking Protocols, Queuing Theory* and *Multi-threaded Task Scheduling* exploring innovative approaches towards introducing tangible interaction design in HEI contexts.

In addition, TUI frameworks such as *Database Normalisation* augment the TUI architecture through the integration of embedded sound interaction, whilst in *Object-Oriented Programming* and *Search-Space Problems,* smart tabletop peripherals extend the interaction design dimensions afforded through TUI frameworks. Furthermore, in TUI adaptations for *Robotic Operating Systems and Artificial Neural Networks*, the tangible paradigm was further protracted through the novel design of active tangible interactions which enriched the capacity of the proposed TUI frameworks to embody different attributes of complex and abstract concepts.

The development of each TUI framework was experimentally evaluated during adequate deployment within undergraduate programmes in HEIs. To derive an objective metric of effectiveness whilst asserting the suitability of TUI frameworks to in the teaching and learning of threshold concepts within HEI contexts, a diverse set of evaluation methodologies was adopted. TUI framework designed for *Database Normalisation, Queueing Theory, Multi-*

threaded Task Scheduling and *Robotic Operating System* were comparatively assessed against educational technologies currently adopted in HEI lectures so as to evaluate the effectiveness of TUI frameworks to engage students within active-learning pedagogies.

Subsequently, evaluation methodologies explicitly investigate the capabilities imparted through the designed tangible interactions in direct assessment counter to the effectiveness achieved from current active-learning pedagogies commonly adopted in seminar and laboratory contexts. The evaluation methodologies adopted for *Object-Oriented Programming* and *Networking Protocols* assess the educational effectiveness of the designed TUI interactions in contrast to current educational platforms adopted in HEI laboratory sessions through dedicated and specialised GUI software. Within *Search-Space Problems*, the exploratory effectiveness obtained through tangible interactions was evaluated with respect to a gamified learning approach deployed on a computer-based web platform. Moreover, the hypothesis of adopting TUIs as a more effective alternative to current HEI educational technologies was further investigated within *Artificial Neural Networks*, whereby an identical WIMP interface was developed for the control group, mirroring virtualisations and interactions through conventional PC peripherals.

Throughout each deployment, a variation was also undertaken on the student group sizes implemented within each evaluation session. Collaborative exercises were provided to group sizes ranging between 2 and 7 students in experimental sessions, allowing the assessment and assertion of collaborative interaction undertaken through the designed TUI frameworks. The variety of evaluation methodologies implemented, progressively outline the augmented learning capabilities derived through the proposed TUI frameworks and extend research contributions in teaching and learning threshold concepts through tangible technology in HEI contexts.

Chapter 6
An Acceptance Modelling Framework for Evaluating Educational Technology

Aiming to evaluate the suitability of adopting Tangible User Interfaces (TUI) in Higher Education Institutions (HEIs), this chapter extends the evaluation aspect of this technology through an appropriate Technology Acceptance Model (TAM) which quantifies the acceptance of TUI in education.

A brief literature review is presented in section 6.1 to analyse the different technology evaluation methodologies used to define user acceptance. The critique covers the evolution of TAM frameworks together with their derivations and extensions whilst outlining their intended use and effectiveness for application purposes. The study delves into more detail towards TAM variants in education in section 6.1.3 and describes through literature the two main areas of model development in this domain: teacher's technology acceptance and online learning platforms. In light of this research, this chapter proposes the introduction of a novel adaption for a Technology Acceptance Model for Education (TAM4Edu), which specifically aims at evaluating the acceptance and suitability of educational technology in higher education. The design and analysis process for the proposed TAM4Edu model are detailed within section 6.2 in light of considerations specific to educational adoption. The designed TAM4Edu model was subsequently deployed within an HEI context to assess and compare the suitability of the proposed TUI frameworks, with respect to alternate educational technology options, currently utilised for HEI tuition. Thus, section 6.3, details the validation study undertaken on the developed architecture followed by an analysis of the TUI acceptance in HEI in comparison to conventional educational technology.

6.1 Technology Acceptance Frameworks

The diffusion and adoption of ICT solutions have been studied in significant detail within the area of information systems from both an organisational and individual level (Masrom, 2007). Within academic and trade literature (Cohen, 2005; Jasperson, Carter and Zmud, 2005) careful considerations in design interventions have been able to effectively maximise IT adoption and use, thus leading to mature and rich theories to explain technological adoption and use decisions (Venkatesh *et al.*, 2003; Sarker, Valacich and Sarker, 2005).

Adoption is defined within these models through interventions along the technology's lifecycle with active stages for considerations in both pre-implementation and post-implementation phases, as described by Cooper and Zmud (1990) and Saga and Zmud (1994):

- Initiation: The derivation of organisational opportunities that warrant a technological solution.
- Adaptation: The modification processes undertaken on individual and organisational needs to better fit the technology within the work setting.
- Acceptance: Individual and organisational efforts undertaken to commit to the use of technology.
- Routinization: Efforts undertaken to reduce the perception of new or out-of-the-ordinary aspects of technology.
- Infusion: The deep embedment of technology within an organisation's work system.

The influence on successful adoption and user acceptance has been highly linked to the information and system-related design characteristics of a technology (DeLone and Mclean, 2003; Wixom and Todd, 2005). The design considerations on information-related aspects of technology help users improve productivity and performance (Dennis and Valacich, 1993; Dennis *et al.*, 1997). In tandem, the intrinsic system-related design goals to provide accurate and timely relevant information displayed in an understandable format, contribute towards enhancing the user's perceived relevance and usefulness towards achieving high-quality result outputs from technology (Speier, Vessey and Valacich, 2003). Coupled with system reliability, flexibility and user-friendliness, these system-related design considerations impart a positive impact on user experience, self-efficacy and confidence in technology (Venkatesh and Bala, 2008).

From a post-implementation perspective, these models indicate technology acceptance in light of the functionality and implementation success obtained by users through their engaging experience (Orlikowski, 2000). Effective design interventions are instrumental towards ensuring users react favourably to the changes brought about by technology on their characteristic behaviour and thus perceive new systems as opportunities to enhance their performance (Beaudry and Pinsonneault, 2005; Boudreau and Robey, 2005).

6.1.1 TAM Framework Introduction

Amongst all the theories of user adoption, the Technology Acceptance Model (TAM) defined by Davis (1989), is the most common ground theory in information systems research (Taylor and Todd, 1995; Šumak, Heričko and Pušnik, 2011). Fundamentally based on the psychological theories of Reasoned Action (TRA) proposed by Fishbein and Ajzen (1975), and the Theory of Planned Behaviour (TRB) (Ajzen, 1985), the model posits that actual usage of technology is driven by behavioural intention. This factor is further defined as a function of an individual's attitude towards technology together with the subjective norms and perceptions surrounding the technology's performance (Ajzen, 1991). Extending on these philosophies, Davies (1986) identified two distinct antecedents; perceived usefulness and perceived ease of use, as being sufficiently able to predict the attitude of users towards the acceptance and usage intention of a system (Davis, Bagozzi and Warshaw, 1989; Venkatesh, Morris and Ackerman, 2000). Thus, technology acceptance was defined as "an individual's psychological state with regard to his or her voluntary or intended use of a particular technology" (Masrom, 2007).

As illustrated in the TAM model depicted in Figure 6.1, usage is determined by *behavioural intention to use*, an output that has been significantly confirmed through theoretical and empirical bases (Adams, Nelson and Todd, 1992; Yi and Hwang, 2003; Karahanna, E., Agarwal, R. & Angst, 2006). Behavioural intention is primarily affected by the *attitude* towards usage as well as the direct and indirect effects of the mediating constructs; *perceived usefulness* and *perceived ease of use* (Liaw and Huang, 2003; Cheung and Huang, 2005). Furthermore, as shown in Figure 6.1, it was postulated in the TAM model that whilst the two fundamental determinants jointly affect usage *attitude* (Davis, 1989), *perceived ease of use* has a direct impact on *perceived usefulness*, which in turn has a direct effect on *behavioural intention to use* technology (Hasan, 2006).

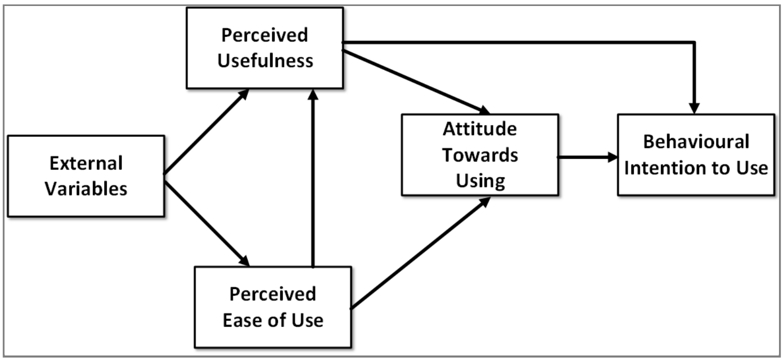


Figure 6.1 Technology Acceptance Model (TAM) architecture illustrating influential effects between determinants through directional vertices (adapted from: Davis, 1989).

A vast amount of literature has analysed the TAM model, with systematic reviews outlining the scale and diversity of evaluation tests and hypothesised considerations (Lee, Kozar and Larsen, 2003; Legris, Ingham and Collerette, 2003; King and He, 2006; Sharp, 2007; Chuttur, 2009; Hsiao and Yang, 2011; Marangunić and Granić, 2015). Throughout these literature studies, the TAM architecture has received empirical support as a robust and parsimonious model (Groves and Zemel, 2000; Pan, Sivo and Brophy, 2003; Teo *et al.*, 2008; Rauniar *et al.*, 2014) with predictive validity across technological tools (Huang, Liaw and Lai, 2016), gender (Padilla-Meléndez, Del Aguila-Obra and Garrido-Moreno, 2013) and cultures (Aypay *et al.*, 2012; Teo, Ursavaş and Bahçekapili, 2012). This research is further published within a cohesive research body and computational literature review on the domain outlines a well-established TAM community connected around a main research component (Mortenson and Vidgen, 2016).

This consolidated literature has led TAM to emerge as the leading ground theory model in explaining and predicting technological adoption (Hidayanto *et al.*, 2014; Hsia, Chang and Tseng, 2014; Lee, Hsiao and Purnomo, 2014; Wu and Zhang, 2014; Al-Gahtani, 2016). Furthermore, extended models of TAM are able to retain a good predictive power across domains, with significant variance in technology usage explained through the behavioural model (Turner *et al.*, 2010; Šumak, Heričko and Pušnik, 2011; Escobar-Rodriguez and Monge-Lozano, 2012; Lin, Persada and Nadlifatin, 2014).

6.1.2 TAM Framework Evolution

Whilst the statistical meta-analysis by King and He (2006) highlighted the robustness and validity potential of adopting the TAM framework in broader applications, various research suggested inconsistent and mixed results on rigour, assumptions and practical effectiveness of the model (Sharp, 2007; Chuttur, 2009). The abstractness of the TAM model has been critiqued for not including significant determinants relating to exploring human, social and boundary factors (Lee, Kozar and Larsen, 2003; Legris, Ingham and Collerette, 2003), thus reflecting the agreement that without external factors the TAM framework does not provide “specific information that can better guide system development” (Mathieson, 1991).

Aiming at addressing these perennial issues, the TAM model was altered by removing the *attitude* construct following the realisation that it could not fully mediate the *perceived usefulness* and *perceived ease of use* of a system (Davis, Bagozzi and Warshaw, 1989). The model’s output was eventually replaced by

Davis (1993) by introducing the *behavioural intention* construct for explaining the direct influence of the perceived determinants as illustrated in Figure 6.2:

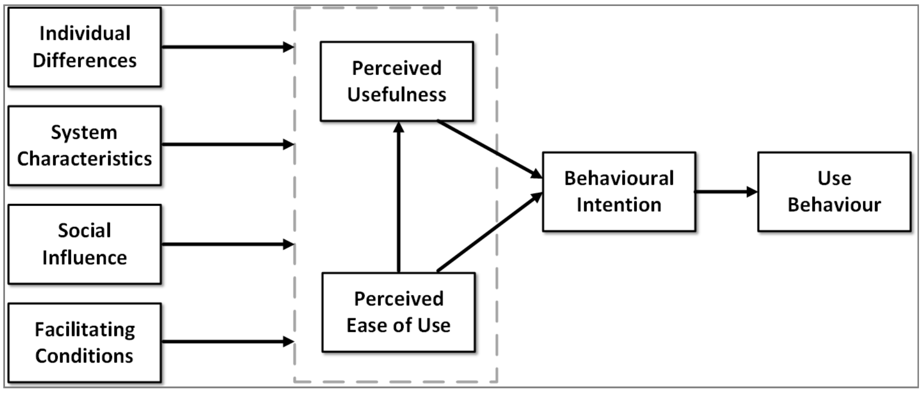


Figure 6.2 Technology Acceptance Model (TAM) architecture illustrating influential effects between determinants through directional vertices (adapted from: Davis, 1993).

Subsequently, Venkatesh and Davis (Venkatesh and Fred D. Davis, 2000) proposed an evolved framework, the Technology Acceptance Model 2 (TAM2) model, within which they identified and theorized about the general determinants of *perceived usefulness*. This factor was explained through the theoretical aspects of social influence and cognitive instrumental processes, with the inclusion of *experience* and *voluntariness* as external moderators. These models were further refined into a set of determinant constructs as illustrated in Figure 6.3. The social influence mechanisms were modelled on the processes of compliance with social norms (Miniard and Cohen, 1979), identification within a group, and internalisation of communal belief (Warshaw, 1980). Conversely, cognitive instrumental processes were designed based on the theories of work motivation (Vroom, 1964), action identification (Vallacher and Wegner, 1987) and behavioural decision (Beach and Mitchell, 1996, 1998) underlying the theoretical argument that individuals "form perceived usefulness judgement in by cognitively comparing what a system is capable of doing with what they need to get their job done" (Venkatesh and Fred D. Davis, 2000).

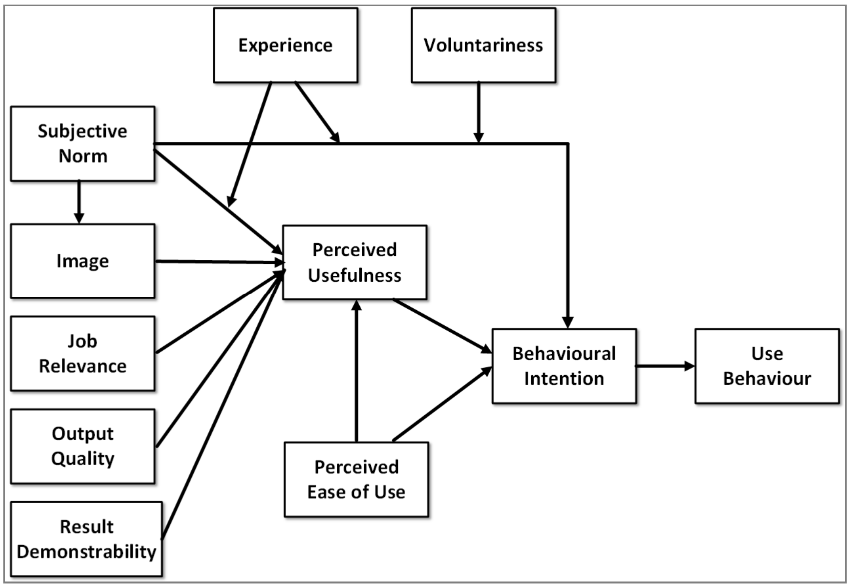


Figure 6.3 Technology Acceptance Model 2 (TAM2) architecture illustrating influential effects between determinants through directional edges (adapted from: Venkatesh and Davis, 2000).

Concurrently, Venkatesh (Venkatesh, 2000) expanded further the list of constructs to model the determinant of *perceived ease of use*. These constructs were designed around the anchoring and adjustment framing of human decision making and relate to the individuals general believes regarding computers and computer use (Venkatesh, 2000). This model of determinants for *perceived ease of use* was combined together with TAM2 architecture (Venkatesh and Fred D. Davis, 2000) in the subsequent evolution the framework defined as Technology Acceptance Model 3 (TAM3) by Venkatesh and Bala (2008).

Based on the action identification theory (Vallacher and Kaufman, 1996), the TAM3 framework differentiates between high-level identities such as individual's goals and plans with respect to low-level identities such as the manner in which these goals are achieved (Venkatesh *et al.*, 2003). Within this distinction, the lower-level constructs reflect information on the user's experience through actions, hence affecting *perceived ease of use*. Conversely, the ability to obtain the individual's high-level impact on the determinants oulines predicates for the *perceived usefulness* construct (Sundaravej, 2004).

The TAM3 model, reproduced in Figure 6.4, expanded the influence of the *experience* moderator and observed various longitudinal effects its relationship to the model's constructs (Venkatesh and Bala, 2008). The TAM3 framework further postulated that no cross-over influential effects are exhibited between the determinants of either *perceived ease of use* or *perceived usefulness*. Whilst Venkatesh and Bala (2008) based their premise on the hypothesis that computer-related traits and emotions do not impact social and cognitive influence processes, this assertion has failed to garner empirical support in wider contexts where numerous external factors provided statistical support to both determinants (Abdullah and Ward, 2016).

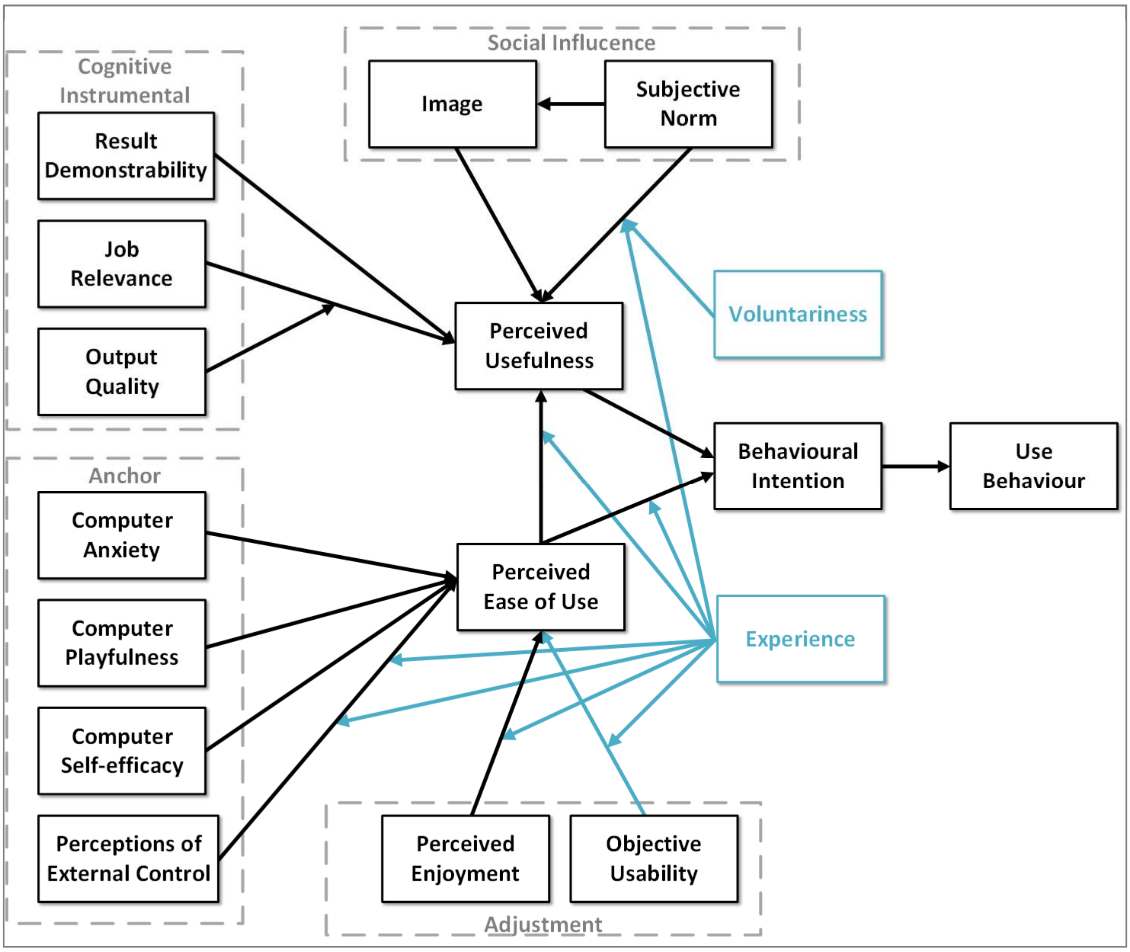


Figure 6.4 Technology Acceptance Model 3 (TAM3) architecture illustrating influential effects between determinants through directional edges (adapted from: Venkatesh and Bala, 2008) highlighting framework constructs (in black) and moderating factors (blue).

6.1.3 TAM Framework Extension

Despite the accolades attributed to the original TAM framework on its empirical validity in a plethora of IT acceptance domains due to its general and context-independent fundamental constructs (Ma and Liu, 2004), the evolutionary stages and developments of the framework were subsequently based on organisational theories (Bacharach, 1989). Thus, this led to the constructs proposed in subsequent models to provide context specificity to the deployment of the TAM architecture (Venkatesh, 2000; Venkatesh and Fred D. Davis, 2000). To this end, the effectiveness of TAM frameworks to predict technology usage outside their designed and validated contexts without thoughtful considerations has often led to unreliable results (Turner *et al.*, 2010).

Dishaw and Strong (1999) denoted the need in TAM deployment for exploring further the nature of specific influences of technological and usage-context factors that can potentially alter the user's acceptance of technology. The need for TAM to include additional variables in order to provide a broader view and better explanation of technology adoption has thus been commonplace through literature critique (Legris, Ingham and Collerette, 2003). Thus, numerous studies propose and evaluate the applicability of external constructs and factors to contextually model the chain of influence these determinants impart on the dependent output variable of *behavioural intention* in TAM frameworks (Cheung and Huang, 2005; Hasan, 2006; Ngai, Poon and Chan, 2007).

As the evolution of the TAM framework coincided chronologically with the proliferation of Internet technology throughout the last decades, research extensions of the model focused heavily the influential factors affecting the adoption of this technology (Moon and Kim, 2001; Shih, 2004; Lee and Kim, 2009). Moreover, various TAM extensions have looked at specific systems such as electronic mail (Serenko, 2008), websites (Castañeda, Muñoz-Leiva and Luque, 2007), search engines (Liaw and Huang, 2003) and social media (Lee, Xiong and Hu, 2012; Rauniar *et al.*, 2014; Wirtz and Göttel, 2016). In tandem with the advancement of communication technology, TAM models were further adapted to characterise the acceptance of emerging technologies such as wireless (Lu *et al.*, 2003; C.-S. Wu *et al.*, 2011) and mobile internet (Hong and Tam, 2006; Son *et al.*, 2012).

Within an industrial context, TAM models were extended in organisations to model the acceptance determinants for integration Information Systems (IS) within workplace settings (Rai, Lang and Welker, 2002; Yi and Hwang, 2003) modelling evaluation variations in deployments such as Computer-Aided Software Engineering (CASE) tools (Rai and Patnayakuni, 1996), information security (Hu, Lin and Chen, 2005; Wang, 2012) and executive IS systems acceptance (Rai and Bajwa, 1997). From a commercial perspective, industry promoted the adoption of TAM frameworks to predict factors such as technology *trust* (Gefen, Karahanna and Straub, 2003; Gefen, 2004; K. Wu *et al.*, 2011) when extending TAM within the domain of internet banking (Chan and Lu, 2004; Nasri and Charfeddine, 2012; Martins, Oliveira and Popovič, 2014) and electronic commerce (Koufaris, 2002; Pavlou, 2003; Fayad and Paper, 2015). The utilisation of information systems within healthcare contexts has further extended TAM models (Melas *et al.*, 2011; Pai and Huang, 2011; Holden *et al.*, 2016) with variants assessing technological acceptance in specific adoptions such as telemedicine (Hu *et al.*, 1999; Xue *et al.*, 2014) and internet-supported medical procedures (Chau and Hu, 2002; Holden and Karsh, 2010).

From a TAM perspective, educational institutions have fundamentally different objectives compared to business organisations (Hu, Clark and Ma, 2003). Whilst the fundamental constructs at the core of the TAM architecture have been empirically validated in educational contexts (Park, Lee and Cheong, 2007; Farahat, 2012), the extension of TAM models have been largely constrained towards the two main aspects of technology acceptance, relating to either to student's acceptance of virtual learning environments or teacher acceptance modelling (Tang and Chen, 2011; Teo, 2011; Marangunić and Granić, 2015; Esteban-Millat *et al.*, 2018).

The domain of online-based learning has received considerable interest in the past years throughout the educational community (Ali *et al.*, 2018; Ibrahim *et al.*, 2018) with various studies analysing extensions of the TAM architecture towards e-learning (Gong, Xu and Yu, 2004; Zhang, Zhao and Tan, 2008; Cheung and Vogel, 2013; Tarhini *et al.*, 2017), massive open online courses (MOOC)s (Waard *et al.*, 2011; Zhou, 2016; Wu and Chen, 2017) as well as mobile-based learning (m-Learning) (Huang, Lin and Chuang, 2007; Sánchez-Prieto, Olmos-Migueláñez and García-Peñalvo, 2016). In tandem with advancements in online computer-based technology for education, recent studies have deployed bespoke TAM extensions to model the acceptance of digital game-based learning (Idris, Mat Sin and Ya, 2015), augmented reality teaching platforms (Balog and Pribeanu, 2016) and the educational use of social media (Rauniar *et al.*, 2014; Teo, 2016; Al-Rahmi *et al.*, 2018). Whilst these implementations define TAM architectures within the educational domain, the intrinsic online nature of these studies curtails the ability for these models to extend towards modelling student's acceptance of educational technology within a lecture environment. The constructors proposed for these models thus lack the ability to resolve the pedagogical influences experienced by students during the collaborative and enriched physical interaction with technology during their studies.

As the key stakeholders in the process of educational transformation (Teo, Ursavaş and Bahçekapili, 2012), the perception and acceptance of educators are principally significant for the effective use and adoption of technology in education (Yuen and Ma, 2008; Baturay, Gökçearslan and Ke, 2017). Various studies have thus concentrated on modelling the external determinants of TAM frameworks specifically for educators through the consideration of personal constructs such as *computer self-efficacy* (Paraskeva, Bouta and Papagianni, 2008), technology factors such as complexity and usability (Thong, Hong and Tam, 2002; Swain, 2006), as well as facilitating environmental conditions (Ngai, Poon and Chan, 2007; Fathema, Shannon and Ross, 2015) for successful adoption of technology within teaching and learning contexts. Albeit extensive literature has been carried out to validate TAM constructs for teachers and educators (Wong *et al.*, 2013; Scherer *et al.*, 2018), these models conceptualise intrinsically the employment and professional aspect of academia, thus rending them unsuitable for adoption in evaluating students' perception of technology (Bennett, Maton and Carrington, 2011). This research gap in the explanatory ability of TAM determinants for modelling the acceptance of educational technology by student users was recently further explicated by Teo (2016) whilst enlisting existential limitations to current educational TAM architectures.

6.2 Designing a TAM for Educational Technology

In light of the constrained scope of TAM frameworks within education and the inability of current TAM models to provide design guidance for the development of educational technologies based on student acceptance in HEIs (Dumpit and Fernandez, 2017), this section proposes the adaptation of a technology acceptance model for educational technology (TAM4Edu). Based loosely on the various TAM model evolutions and extensions defined in the literature, the proposed architecture is underpinned on empirically validated TAM architecture as illustrated in Figure 6.5:

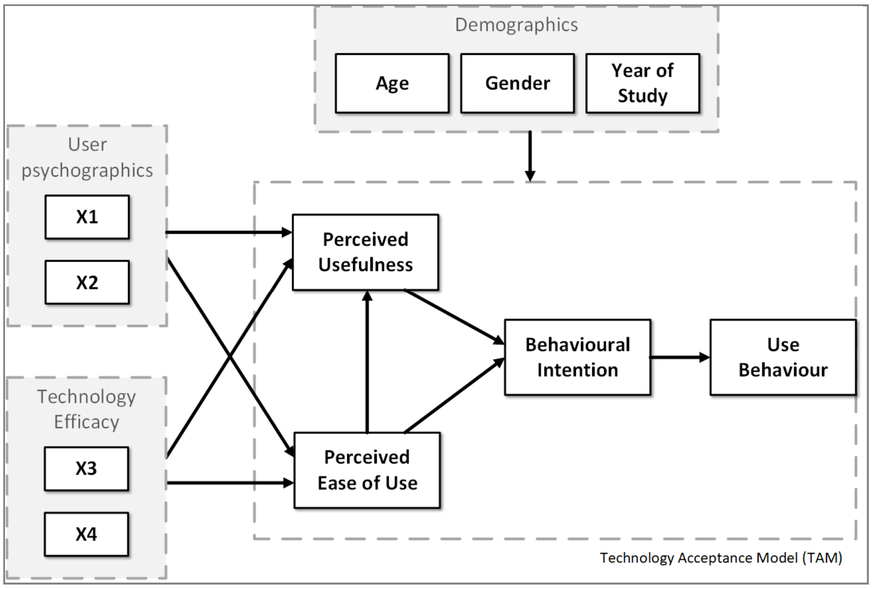


Figure 6.5 TAM4Edu architectural model.

The determinants for integration within TAM4Edu were identified from literature extensions and as described in section 6.2.1. Questions for these constructs were adapted for use within the context of educational technology and a first-stage data analysis undertaken on the model item set to refine the selection as detailed in section 6.2.2. The design of the proposed TAM4Edu framework is subsequently elaborated in section 6.2.3 describing the framework composition together with relational hypothesis underpinning the proposed model's extension for educational technology acceptance.

6.2.1 Construct Selection

Aiming at contextualising TAM4Edu towards educational technology, a review of relevant constructs from various TAM extensions in literature was undertaken to identify pertinent determinants for inclusion in the model's educational context as described in the list hereunder:

- **Perceived Usefulness -** Originally defined by Davis (1993) as; "the degree to which a person believes that using a particular system would enhance his or her job performance", this determinant is fundamental construct of every TAM model (Marangunić and Granić, 2015) and has a direct influence on the user's behavioural intention for technology acceptance of the system (Davis, Bagozzi and Warshaw, 1989). Thus, Perceived Usefulness (PU) significantly influences technology adoption and usage (Morris and Venkatesh, 2000; Musa, 2006; Ndubisi, 2007; Venkatesh and Bala, 2008).
  Whilst prominent research has investigated the influence of technological factors on this construct within business contexts (Boumediene and Kawalek, 2008), few studies have investigated the usefulness of technology acceptance in education (Macharia and Nyakwende, 2010). To this end, this study has adopted the PU construct to reflect the perceived learning enhancement experienced by students through using educational technology.
- **Perceived Ease of Use -** As the other fundamental belief construct in TAM models, Perceived Ease of Use (PEU) was described by Davis (1993) as; "the degree to which using a particular system would be free from effort". This construct has an influencing effect on PU (Hasan, 2006) and directly influences technology adoption and behavioural intention (Cheung and Huang, 2005; Al-Adwan, Al-Adwan and Smedley, 2013). The construct has been notably decomposed into external determinants in Venkatesh (Venkatesh, 2000) and subsequently integrated within the

TAM3 extension with various anchor and adjustment factors (Venkatesh and Bala, 2008). This core determinant was implemented in the proposed model following contextual adaption to the use of educational technology by students.

- **Behavioural Intention -** The construct of Behavioural Intention (BI) embodies the fundamental assertion of TAM architectures where intention asserts a proper proxy to examine and predict a user's behaviour towards a technology or system. BI was defined originally by Venkatesh and Davis (Venkatesh and Fred D. Davis, 2000) as "the degree to which a person has formulated conscious plans to perform or not perform some specified future behaviour". This construct served as an alternative to *attitude towards using technology* in TAM (Davis, 1993) and is largely based on the Theory of Reasoned Action (TRA) and the Theory of Planned Behaviour (TPB) models (Venkatesh, 1999). The determinant has been adopted in the proposed model in line with the contextualisation of behavioural intention in educational TAM research (Park *et al.*, 2009; Lu, Lin and Chen, 2017; Sánchez-Prieto, Olmos-Migueláñez and García-Peñalvo, 2017).
- **Perceived Enjoyment -** Based on intrinsic motivation (Ryan and Deci, 2000), the concept of Perceived Enjoyment (PEU) is defined within education as "the extent to which the activity of using computers is perceived to be enjoyable in its own right, aside from any academic consequences that may be expected" (Louw, Swart and Bere, 2016). Originally formalised by Venkatesh (Venkatesh and Fred D. Davis, 2000), this determinant has been widely adopted within TAM extensions (Lee, Cheung and Chen, 2005; Yang and Lin, 2011; Park, Son and Kim, 2012) and has been well evaluated for its ability to explain a higher degree to intention to use technology (Cheng, 2011; Zare and Yazdanparast, 2013). The construct is linked to the positive perceptive effects derived from engaging with a system once students believe that using the

technology is enjoyable (Cheng, 2012) and previous research has shown that PEU in students significantly impacted perceptions of about ease of use and usefulness of a system (Sun and Zhang, 2006; Al-Aulamie *et al.*, 2012). Within the context of educational technology, this construct has thus been adopted to evaluate the enjoyment derived by students in utilising educational technologies within their lecture environment.

- **Computer Self Efficacy -** Derived from the psychological metric of Self-Efficacy (SE), which evaluated a person's individual judgement on their own capabilities to organise and execute courses of action required to achieve a specific goal (Alfred Bandura, 1977; Bandura, 1982), this construct was originally contextualised for computer technology as "the user's degree of belief on personal ability to accomplish a particular task using computers" (Compeau and Higgins, 1995). The determinant is based on the premise that users who consider computers too complex may avoid adopting the technology if they lack the ability to operate the system (Igbaria and Parasuraman, 1989; Shen and Eder, 2009).

  Prior TAM research hypothesizes that Computer Self Efficacy (CSE) has a direct influence on the individual's perception of technology's ease of use and consequently acceptance decision (Yuen and Ma, 2008; Moghadam and Bairamzadeh, 2009; Hsia, Chang and Tseng, 2014). Gong, Xu and Yu (2004) further outline that prior to users undertaking hands-on experience of a new technology or system, the general perception of this construct serves as an anchor for user's perception of how easy the technology is to use. This construct was thus adopted within the proposed model to evaluate the student's self-efficacy in engaging with computer-based educational technology during their study.
- **Technology Anxiety -** The determinant of Technology Anxiety (TANX) is defined in the context of computer usage as "the tendency of an individual to be uneasy, apprehensive, or fearful about the current or

future use of computers in general" (Igbaria and Parasuraman, 1989). Originally adapted within the TAM2 model as Computer Anxiety (CA) by Venkatesh and Davis (Venkatesh and Fred D. Davis, 2000), the construct aims to capture the anxious or emotional reactions evoked on users when interacting with technology (Venkatesh *et al.*, 2003). The effects of this determinant have been widely associated with reluctance and avoidance of using technology (Al-Alak and Alnawas, 2011; Purnomo and Lee, 2013) and thus the construct plays a significant role in characterising the user adoption of technology (Alenezi, Karim and Veloo, 2010).

Nevertheless, the longitudinal study by Venkatesh and Davis (Venkatesh and Fred D. Davis, 2000) outlined that through time and experience the element of anxiety diminishes in users, reducing the overall effect of the determinant on PEU in favour of constructs such as *usability* and *perceived enjoyment* (Reed and Overbaugh, 1993). Considering the above, this determinant has been included in the proposed model to represent the potential anxiety effects of introducing novel technology within education and further describe the compositional construct of students *Behavioural Intention*.

- **Usability -** Based largely on the heuristic guidelines by Jakob Nielsen (1994) and Shneiderman (2010), the determinant of Usability (USE) aims to encapsulate the users requirements for effectiveness, efficacy, utility, learnability and memorability in technology (Holden and Rada, 2011; Preece, Rogers and Sharp, 2015). The critical aspect of this determinant has commonly led to non-acceptance and failure of technological adoption (Seffah *et al.*, 2006; Scholtz *et al.*, 2016). To this end, several quantitative methods have been provided to measure this metric in organisational structures such as; the *Software Usability Measurement Inventory (SUMI)* (Kirakowski and Corbett, 1993), the *System Usability Scale (SUS)* (Brooke, 1996) and the *USE* questionnaire (Lund, 2001). Within TAM architectures, Venkatesh (Venkatesh, 2000) provided the most noted extension for USE, as he identified key determinants to *perceived ease of use*. Alas, the metric was adopted as objective usability and evaluated only as a ratio of time between duration of task undertaking between teachers and students, without accounting for the user's subjective perception of usability (Venkatesh, 2000).

The importance of usability within the educational domain has long been emphasised (Holden and Rada, 2011) and the lack of pedagogical support within technological systems often attributed to educational failure (Wade, Wade and Lyng, 2000; Sugar, 2001; Bower, 2006). Albeit this understanding, the literature on the usability of educational software remains scarce (Williams, Boone and Kingsley, 2004; Scholtz *et al.*, 2016) and thus the proposed model aims to adapt the construct to determine the effect of usability in educational technology towards enhancing the teaching and learning pedagogy.

- **Social Interactivity -** The effect of social cognitive theory (Bandura, 1986) has been validated by many empirical studies on its effect on computer skill acquisition (Gist, Schwoerer and Rosen, 1989; Mitchell *et al.*, 1994) and user acceptance of technology (Agarwal, Sambamurthy and Stair, 2000; Venkatesh, 2000) as an external mediation variable (Yi and Hwang, 2003; Burton-Jones and Hubona, 2006). In line with the socio-psychological theories of learning (Albert Bandura, 1977; Karahanna, Straub and Chervany, 1999) however, social-contexts were deemed to impart an influential factor on the usefulness of educational technology. Thus, to measure the pedagogical effectiveness of educational technology to student learning, Social Interactivity (SOCINT) was adopted as a direct determinant in the proposed model.
- **Perceived Lecture Attention -** The determinant of Perceived Lecture Attention (PLA) was postulated in the proposed model to integrate the Attention, Relevance, Confidence and Satisfaction (ARCS) model (Keller, 1983) later extended with the Visual, Aural, Read/Write and

Kinesthetic (VARK) questionnaire (Fleming and Baume, 2006). The former model investigates the interest gained by students both through perceptual and inquiry arousal which are stimulated through surprise, problem-solving and challenging tasks (Keller, 1983, 1999, 2010). Researchers have adopted the VARK modalities to provide visual and auditory appeal as motivators in teaching and learning contexts (Colakoglu and Akdemir, 2010; Urval et al., 2014; Louw, Swart and Bere, 2016) based on educational psychology (Lepper and Chabay, 1985; Felder and Silverman, 1988; Lepper, 1988). In line with this educational research, the proposed model defines the PLA determinant to analyse the effect of educational technology to motivate student attention to engage in academically productive activities.

- **Study Relevance -** The development of the Study Relevance (STREL) determinant stems from the adaptation of Job Relevance and Output Quality constructs defined within the industry oriented TAM2 model (Venkatesh and Fred D. Davis, 2000). Albeit literature on the adaption of these constructs to education is scarce, with the exception of Macharia and Nyakwende (2010) who developed a determinant for assessing the relevance of emails to student studies, the proposed model describes the determinant construct to reflect the efficacy of educational technology to deliver value in relation to the students education. This construct is considered influential in users' behavioural intention towards adopting the technology, especially for more mature HEI students in determining the technologies usefulness.

The definitions for the above constructs were subsequently adapted towards the pursuit of technology in educational contexts. This contextualisation enabled the selection of pertinent constructs towards the proposed model whilst discarding or readjusting commonly used constructs such as; Job Relevance, Output Quality and Image. Hence, the updated constructs relevant for a TAM4Edu model are summarised in Table 6.1:

Table 6.1: Definitions of TAM4Edu adapted constructs

Determinant	Acronym	Definition	Adapted From
Behavioural Intention	BI	The degree of student intention to use the educational technology again in the future.	Venkatesh and Davis (2000)
Perceived Usefulness	PU	The degree to which a person believes that using educational technology enhances his or her learning efforts.	Davis (1993)
Perceived Ease of Use	PEU	The degree to which using the educational technology is free from effort.	Davis (1993)
Perceived Enjoyment	PENJ	The extent to which the activity of using an educational technology is perceived to be enjoyable in its own right, aside from any performance consequences resulting from system use.	Venkatesh (2000)
Computer Self-Efficacy	CSE	The user's degree of belief on personal ability to accomplish a particular task using educational technology.	Compeau & Higgins (1995)
Technology Anxiety	TANX	"The degree of an individual's apprehension or fear when interacting with educational technology.	Venkatesh & Bala (2008)
Usability	USE	The degree of technology's interactivity which students perceive aids in effective learning through the system.	Holden & Rada (2011)
Social Interactivity	SOCINT	The degree of interactivity and team collaboration which was effectively mediated through educational technology.	Venkatesh (Venkatesh, 2000)
Perceived Lecture Attention	PLA	The degree to which educational technology enabled the student to remain focused during the lecture.	Fleming & Baume (2006)
Study Relevance	STREL	The degree to which a student feels that using the educational technology supports his study pursuit.	

Each construct was expressed through a number of questions aimed towards eliciting the student's perception towards the identified determinants as tabulated in Table 6.2. An extensive set of determinant specific questions was adapted from literature models to reflect contextualization within the educational domain. A subset of determinants, such as *Social Interaction* and *Perceived Lecture Attention*, were designed to characterise the unique aspects of educational technology adoption, whilst, constructs such as *Study Relevance* and *Usability* were also adapted to replace industry-specific alternatives currently available TAM frameworks. The phrasing of each question was adapted in consultation with a group of educational practitioners at Middlesex University, and ratified after first-stage validation as described in section 6.2.2 .

Table 6.2: Evaluation Questions adapted for each identified determinant

Construct	Acronym		Evaluation Question
Perceived Usefulness	PU1		I was able to fulfil all given tasks using the operators available.
	PU2		The technology used in this lecture helped me understand the subject effectively.
	PU3	(R)	I wasn't able to learn the subject effectively through the technology used.
	PU4		The lecturing technology used today enabled me to better understand abstract material.
	PU5	(R)	This educational technology is not suitable to study with.
Perceived Ease of Use	PEU1	(R)	The used technology was rather difficult to operate.
	PEU2		The procedures used on the technology replicated the ones I use on my personal devices (tablets, smartphone etc.).
	PEU3		Performing tasks using the technology is intuitive
	PEU4		The inbuilt helping tips, helped me finishing the task effectively.
	PEU5		Overall, I find the technology easy to use
Behavioural Intention	BI1		I look forward to using the same technology again in the near future.
	BI2		The lecturing technology used in this lesson should be used regularly.
	BI3		The used technology should be made available after lecturing hours.

Construct	Acronym		Evaluation Question
Computer Self-Efficacy	CSE1		I was able to finish the given task using the technology without supervision.
	CSE2	(R)	I needed someone to show me how the technology functions first.
	CSE3		It is easy for me to remember how to perform tasks using the technology.
Technology Anxiety	TANX1		Educational technology (interactive boards, PCs, etc.) do not scare me.
	TANX2	(R)	Technology in general makes me nervous.
	TANX3		I felt comfortable using the educational technology.
	TANX4	(R)	Technology in general makes me feel uneasy.
Perceived Enjoyment	PENJ1		The feedback I have received from the lecturing technology made my experience enjoyable.
	PENJ2	(R)	The used educational technology was boring.
	PENJ3		The actual process of using this lecturing technology was enjoyable.
	PENJ4		I had fun using the educational technology.
Study Relevance	STREL1		I find the use of such technology as important in my studies.
	STREL2		I have no problem with the quality of the technology's output.
	STREL3		The output quality I have got from this technology was high.
	STREL4		Using the educational technology was relevant to my studies

Construct	Acronym		Evaluation Question
Usability	USE1		I find the information from the educational technology used to be very intuitive.
	USE2		Learning how to perform tasks using the technology was easy
	USE3	(R)	I waited a long time to get feedback from the educational technology.
	USE4		The feedback from interacting with the system was intuitive.
	USE5		I could tell when the lecturing technology was waiting for my input.
	USE6		The technology / system sensed my movements.
	USE7		Operating the educational technology was intuitive.
Social Interactivity	SOCINT 1		Through the lecturing technology I have learned to work in a team.
	SOCINT2		The lecturing technology promoted discussion and collaboration with classmates.
	SOCINT3		The used technology permitted me to interact with my class mates.
Perceived Lecture Attention	PLA1		I felt very attentive during this lecture.
	PLA2	(R)	I have gotten distracted during the lecture.
	PLA3		Through this lecture I would characterise myself as being concentrated.

**Evaluation Questions marked in (R) are Reverse Code*

6.2.2 First Stage Data Analysis

6.2.2.1 Collection Methodology

A preliminary question set based on the above constructs was distributed online to students making use of the Google Form attached in Appendix C.1. Participants scored their degree of agreement to each item, using a 7-point Likert scale (Venkatesh *et al.*, 2003; Sundaravej, 2004), ranging from 1 (strongly disagree) to 7 (strongly agree). The order of questions from all constructs was randomised within the model's questionnaire, to avoid potential bias in unengaged responses between constructs. Furthermore, to detect such instances, a random set of questions marked in Table 6.2 with an *(R)*, were intentionally reverse coded to expose such behaviour whilst ensuring that students were still engaged with the question answering (Teo, 2009; Brezavšček, Šparl and Žnidaršič, 2014). In addition, the survey collected participants' demographic data such as; gender, age and enrolled year of programme study for moderation analysis, within a separate section of the questionnaire (Teo, 2016).

Data collection on the initial constructor question set, was undertaken through supervised online participation by volunteering students reading undergraduate programmes within science and technology at Middlesex University Malta. No reward in monies or kind was given to participants, who took no more than 20 minutes to complete the questionnaire. The latter was written in English and administered during the university's study term after a set of lectures and seminars in which students were engaged with the use of different educational technologies. A total of 99 participants volunteered to the study, who provided consent in line with the university's research ethics process for anonymous data gathering, on their personal experience when using educational technology.

6.2.2.1 Data Screening

Data screening was performed on the respondent's dataset by analysing the engagement of each student on the questionnaire statements. Instances of missing data were identified and participants who neglected more than 25% of the survey questions (six responses) were subsequently omitted from the study. The omissions of these participants were visually analysed to understand the propensity of the missing data and ascertain their Missing at Random (MAR) characteristic. Unfortunately, all six participants exhibited contingent omissions present within entire sections of their questionnaire responses. Due to the blended manner in which determinant question where allocated through the survey, this phenomenon led to understand that the omissions where influenced through external factors to the question data and thus responses from these participants could potentially contribute to misleading data within acquired dataset.

In other instances, missing values within participant results were imputed with data representing the median value of each respective question. Subsequently, the dataset was analysed for unengaged responses by students by analysing the standard deviation of the questionnaire answers. Participants who did not provide a suitable degree of variance in their answers ($\sigma < 0.5$) were removed (one response). This approach ensured that participants who were unengaged with the questionnaire did not impart bias in the model analysis by providing invariant data between constructs effects (Lowry and Gaskin, 2014).

The nature of the designed model yielded nonmetric data variables on a Likert domain to assessment questions, and thus no exclusions were performed on outliers since all acquired ordinal responses provided equal relevance. Moreover, the model adopts a categorical enumeration for gender and year of study inputs, thus mitigating potentially erroneous data entry. Moderating factors were collected using nominal variables for socio-demographic data, shown in

Table 6.3, and thus outliers did not constitute abnormal/erroneous data with respect to the model's scope.

Table 6.3: The socio-demographic profile data of survey participants

Age		Educational Level	
Between 16 to 25 years	62	Undergraduate 1st year	11
Between 26 to 35 years	28	Undergraduate 2nd year	34
Between 36 to 45 years	2	Undergraduate 3rd year	48
Over 46 years	1		
mean:	24.6 *years*	Educational Technology Used	
(N=93)	(σ = 6.13)	PC based Software	24
		Tangible User Interface	55
Gender		Smartboard and Projector	14
Male	83		
Female	10		

6.2.2.2 Descriptive Statistics

The mean values of all the 41 questions utilised in the first stage study, were above the mid-point of 4.0 (neutral) and ranged from 4.30 to 6.65. This indicated that participants had generally positive responses towards the assessment questions used to measure the research variables on technology acceptance (Teo, 2016). Furthermore, the standard derivations ranged from 0.713 to 1.75, indicating a fair spread of scores around the respective mean of each construct.

A frequency analysis on the dataset was also performed to analyse the skewness and kurtosis effects on each independent question. With the exception of items highlighted in

Table 6.4, the skewness and kurtosis values of all other questions ranged between -2.16 to -0.09 and -0.97 to 4.82 respectively. Thus, univariate normality in data could be assumed on these items since their skewness and kurtosis values were distributed within the recommended cut-offs of ±3.0 and ±6.5 respectively (Kline, 2011).

Table 6.4: Descriptive Statistics for items with high skewness and kurtosis values

Construct Question	N	Median	Variance	Skewness	Std. Error of Skewness	Kurtosis	Std. Error of Kurtosis
TANX1	93	7	1.23	-3.252	.250	12.385	.495
TANX3	93	7	0.51	-2.607	.250	8.273	.495
TANX4	93	7	1.65	-2.614	.250	6.775	.495

The three questions highlighted in

Table 6.4 show that the *TANX* determinant had high kurtosis values within the model's primary data collection. This implied that the frequency distribution of scores for students in higher education on this determinant was very small and highly centred around the median (Lowry and Gaskin, 2014). A visual observation of the dataset confirmed the obtained high positive values by revealing that there was very little variance on appraisal scores within the population which were tightly centred around the rating of 7 (Strongly Agree). This abnormality illustrates that the volunteering respondents, all of whom were undergraduate students enrolled in Science and Technology programmes, felt very comfortable with using a range of educational technologies within their study. This result, obtained on a student population with mean age of 23.6 (σ = 6.1), correlates with the adaptability expectations of 'digital natives' in HEIs (Gu, Zhu and Guo, 2012; Šorgo *et al.*, 2017). However, whilst the relevance of the *Technology Anxiety* determinant is plausibly diminishing through time, the construct was deemed to be appropriate in a wider adaption of a TAM4Edu model, due to potential bias introduced through student demographic variation within this research.

6.2.2.3 Factor Analysis

A Kaiser-Meyer-Olkin (KMO) test was adopted for factor analysis sampling adequacy. As outlined in Table 6.5, a population of variance analysis of 0.781, significantly higher than the 0.6 threshold commonly adopted for this analysis, indicates that 78% of the variability between questions can be explained by underlying factors. On Bartlett's test of sphericity, the chi-squared distributed questionnaire items are correlated together at a statistically significant value ($\rho>0.001$). This asserts a good interrelation between the survey questions, yielding to a factor analysis possible on the underlying relational factors (Williams, Onsman and Brown, 1996).

Table 6.5: KMO and Bartlett's Test factor analysis on construct model

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.781
Bartlett's Test of Sphericity	Approx. Chi-Square	2494.971
	df	820
	Sig.	.000

A Cronbach's reliability analysis was conducted independently for each set of questions relating to the individual constructs. The subscale's alpha levels were optimised through this analysis by identifying survey questions which did not contribute towards the factor's internal consistency. These were removed from the initial version of the framework so as to raise the Cronbach's alpha coefficient for subscale reliability whilst curtailing the length of the eventual survey. The latter was particularly important since as observed from the data screening analysis, students degraded their grading quality towards the end of the original survey with a significant sample providing missing answers in their submissions. Thus, each construct set was optimally trimmed to achieve the inter-item reliability values outlined in Table 6.6

Table 6.6: Cronbach's alpha coefficient for preliminary determinant questions

Construct Factor	Cronbach's Alpha
BI	0.758
CSE	0.710
PENJ	0.806
PEU	0.561
PLA	0.771
PU	0.814
STREL	0.714
SOCINT	0.878
TANX	0.971
USE	0.768

The resultant alpha level for almost all of the construct factors, was above the acceptance value of 0.70 (Bagozzi and Yi, 1988), indicating a suitable inter-item reliability between questions of each determinant. As highlighted in Table 6.6, the only exception for this status was the subscales for *Perceived Ease of Use* which had an alpha level of 0.561, which indicated that the construct questions did not have an adequate level of inter-item reliability. Further analysis on each respective data set found that deleting any additional item would not have significantly increased the alpha levels of the respective construct, since the determinant factor had already been trimmed from an original alpha of 0.362. Thus, a rephrasing exercise was conducted to refine the adaption of the selected determinant's questions in relation to their ease of use and operation as educational technology.

Together with these results, all questions representing every determinant in the model were examined through a bivariate correlation analysis which quantified the functional dependencies and representation of each question towards its determinant. Average correlations were extracted for every question based on the respective Pearson correlation coefficients, with related construct items as shown in

Table 6.7. Moreover, in light of the statistically significant Bartlett's test of sphericity, extracted in Table 6.5, exploratory factor analysis was undertaken on all the model items to extract the individual factor loading scores, together with the extracted commonalities for each item's variance proportion that can be explained by these factors (Armentano, Christensen and Schiaffino, 2015). The factor analysis was undertaken on SPSS using a principal axis factoring extraction for eigenvalues greater than 1.0 and suppressing item loading coefficients of less than 0.3 (Lowry and Gaskin, 2014). An oblique rotation was undertaken on the factors to account for the potential inter-factor correlation typical of Likert-scale type data (Gignac, 2009).

This factor analysis, further detailed in

Table 6.7, allowed the identification of patterns within the model's dataset by highlighting the relevant similarities in each component, through numerous metrics and thus aided the analysis for a smaller set of salient items in the model (Camilleri and Camilleri, 2017). A dimensionality reduction exercise was subsequently undertaken to reduce the number of questions asked for each determinant using the collated analysis results. This ensured that each factor was further optimized with respect to the internal reliability and correlation relationships between questions.

Table 6.7: Factor analysis results for individual construct items

Question Selection	Construct Item	N	Mean	Std. Deviation	Pearson Correlation Average *	Factor Loading	Extracted Item Communality
✓	BI1	93	6.14	1.14	.584	0.870	.778
✓	BI2	93	6.16	1.02	.489	0.977	.627
×	BI3	93	5.67	1.40	.459	0.645	.499
✓	CSE1	93	5.25	1.36	.518	0.838	.653
✓	CSE2	93	5.59	1.34	.421	0.786	.545
×	CSE3	93	5.17	1.36	.409	0.962	.585
×	PENJ1	93	5.91	1.52	.380	0.394	.532
✓	PENJ2	93	5.71	1.20	.558	0.301	.653
✓	PENJ3	93	6.08	1.27	.571	0.818	.849
×	PENJ4	93	6.20	1.04	.508	0.492	.550
✓	PEU1	93	4.88	1.36	.138	0.302	.258
×	PEU2	93	5.59	1.56	.120	0.669	.528
✓	PEU3	93	5.76	1.09	.222	0.433	.596
×	PEU4	93	4.30	1.73	-.031	0.506	.239
✓	PEU5	93	5.49	1.23	.214	0.636	.624
✓	PLA1	93	5.89	1.17	.552	0.763	.707
×	PLA2	93	5.46	1.45	.472	0.840	.539
✓	PLA3	93	5.82	1.12	.548	0.773	.680
×	PU1	93	5.84	1.16	.295	0.471	.497
✓	PU2	93	5.86	1.08	.514	0.910	.781
✓	PU3	93	5.94	1.29	.466	0.943	.638
✓	PU4	93	5.92	1.01	.454	0.777	.655
×	PU5	93	5.92	1.34	.280	0.555	.595
×	SOCINT1	93	4.92	1.60	.579	0.568	.564
✓	SOCINT2	93	4.43	1.76	.642	0.903	.767
✓	SOCINT3	93	5.04	1.55	.726	0.898	.839
✓	STREL1	93	5.83	1.11	.486	0.814	.759
×	STREL2	93	5.53	1.44	.390	0.619	.661
×	STREL3	93	5.87	0.96	.454	0.629	.670
✓	STREL4	93	5.62	1.28	.377	1.175	.567
✓	USE1	93	5.86	1.05	.345	0.831	.736
✓	USE2	93	5.83	0.98	.388	0.663	.459
×	USE3	93	5.26	1.52	.221	0.334	.476
✓	USE4	93	5.70	1.28	.458	0.882	.861
×	USE5	93	5.60	1.01	.261	0.607	.329
×	USE6	93	5.55	1.20	.402	0.498	.661
✓	USE7	93	5.53	1.23	.331	0.848	.633
✓	TANX1	93	6.39	1.29	.535	1.010	.973
✓	TANX2	93	6.30	1.28	.551	0.957	.957
×	TANX3	93	6.65	0.72	.150	0.773	.619
×	TANX4	93	6.46	1.11	.437	0.940	.651

6.2.3 The TAM4Edu Framework

Based on the first-stage analysis of questions and the experience obtained through execution and observation of technology assessment in an educational context, a technology acceptance model for educational technology (TAM4Edu) was designed within this study. This aimed to describe the determinant factors within an educational context to investigate the effective adoption of technology within this domain. Extending the core constructs of a TAM with adapted determinants in section 6.2.1, the proposed model is defined by four categories of hypotheses as illustrated visually in Figure 6.6.

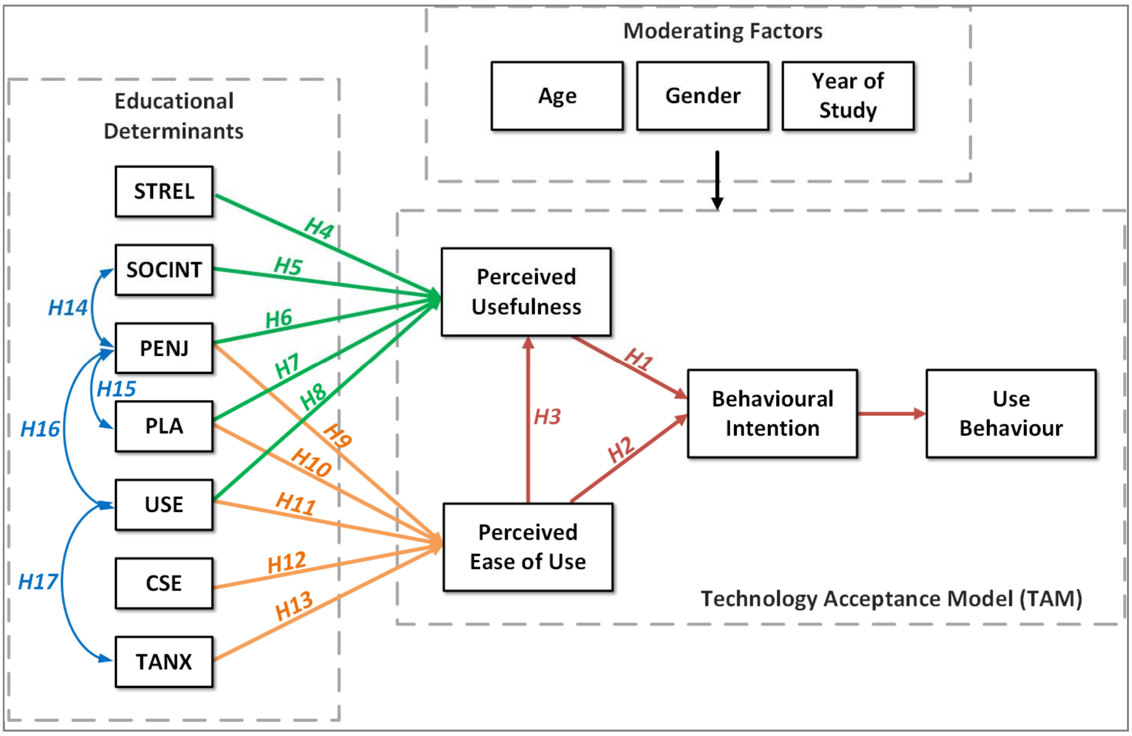


Figure 6.6: Hypothesis visualisation of the proposed TAM4Edu framework including:
- *Technology Acceptance Modelling (red),*
- *Determinants of Perceived Usefulness (green),*
- *Determinants of Perceived Ease of Use (yellow),*
- *Intercorrelated dependencies between determinants (blue).*

In accordance with the relationship model for TAM architecture, the first set of hypotheses (*H1 – H3*) aim to confirm the expression of the proposed framework in accordance with the TAM architecture robustly validated in the literature (King and He, 2006). Thus, the following descriptors were defined for hypotheses testing:

- ***H1: Perceived usefulness will have a statistical positive influence on behavioural intention.***

  This hypothesis validates that the adoption of technology in education necessitates providing a significant positive perception to students on its educational usefulness (Venkatesh and Bala, 2008). Thus, the acceptance of educational technology stems from the ability to provide students with an enhanced learning experience, which facilitates their knowledge acquisition and problem-solving capabilities.

- ***H2: Perceived ease of use will have a statistical positive influence on behavioural intention.***

  The ability of students to easily interact and use educational technology is a critical determinant for sustaining the intention of learners to adopt the technology (Al-Adwan, Al-Adwan and Smedley, 2013). The expectations of university students to effortlessly learn and utilise new technology solutions, further underlines this hypothesis. Thus, technology acceptance is strongly dependent on the design considerations that are undertaken to facilitate and enrich students' experience of interaction with educational technology.

- ***H3: Perceived ease of use will have a statistical positive influence on perceived usefulness.***

  Students' capabilities to easily employ educational technology within their learning pursuit will aid in the technology's useful perception (Davis, 1989). This hypothesis reflects the ability of students to understand complex concepts through the effective use of technology. The relationship thus represents the capability of educational technology to aid students in conceptual understanding without distracting their attention to use the technology.

The relationships outlined in Figure 6.6 in green, represent the hypotheses regarding educational determinants for *Perceived Usefulness*. In line with literature definitions of constructs and their adoption within an educational context, the following hypotheses were formulated:

- ***H4: Study relevance will have a statistical positive influence on perceived usefulness.***

  The assessment of *Perceived Usefulness* by students will be significantly correlated with the ability of educational technology to assist in their studies. This hypothesis asserts that educational technology should ensure a pedagogical approach to aid in the teaching and learning of concepts thus enabling a more effective apprehension of learning outcomes.

- ***H5: Social interaction will have a statistical positive influence on perceived usefulness.***

  The hypothesis describes the ability of educational technology to engage students in social and collaborative learning. In line with social-psychological theories of learning (Albert Bandura, 1977), this hypothesis asserts that educational technology should enhance the ability for students to engage in effective learning pedagogy and thus positively influence their perceived usefulness on the utilised technology.

- ***H6: Perceived enjoyment will have a statistical positive influence on perceived usefulness.***

  The hypothesis asserts that students will positively correlate usefulness of a system with the enjoyment derived in utilising the educational technology during their studies. The perceived enjoyment obtained by students through interaction, will influence their behavioural intention to utilise the technology within their studies.

- ***H7: Perceived lecture attention will have a statistical positive influence on perceived usefulness.***

  In line with the learning theories within the ARCS model (Keller, 1999), the increase in perceived lecture attention through educational technology, will statistically correlate with the students' perceived usefulness in internalising knowledge. This proposition is derived from an adaptation of VARK theory (Fleming and Baume, 2006), whereby the different modalities embedded within educational technology impart a positive influence on the students' ability to engage in academically productive activities.

- ***H8: Usability will have a statistical positive influence on perceived usefulness.***

  This assertion is founded on the principles of design theory which postulates the influence of this factor towards the effectiveness and usefulness of a system (Baskerville and Pries-Heje, 2010). Thus, the usability factor of educational technology should positively correlate to the usefulness perceived by students in employing and engaging with technology to aid their studies.

The identified determinant relationships for *Perceived Ease of Use*, notated in orange within Figure 6.6, represent the constructs adopted within TAM4Edu according to the following hypotheses:

- ***H9: Perceived enjoyment will have a statistical positive influence on perceived ease of use.***

  Based on the positive engaging effects noted by Cheng (2012) on users engaging with technology once they believe its enjoyable, this hypothesis describes the positive correlation of perceived enjoyment on perceived ease of use.

- ***H10: Perceived lecture attention will have a statistical positive influence on perceived ease of use.***

  The hypothesis correlates the positive effect on lecture attention asserted in the ARCS model (Keller, 1983) by students, through the perceptual engagement and inquiry arousal in using a system. The adoption of VARK modalities in educational technology, thus enhances the students' ease of use with computing systems allowing for the provision of more effective educational outcomes.

- ***H11: Usability will have a statistical positive influence on perceived ease of use.***

  The hypothesis asserts a positive correlation between the effect of usability as a determinant to the perceived ease of use in interacting with educational technology. Based on the fundamentals of design heuristics (Nielsen, 1994), this proposition underlines the psychological factors of interactivity, navigation and learnability in educational technology to positively influence students' perceived ease of use.

- ***H12: Computer self-efficacy will have a statistical positive influence on perceived ease of use.***

  In tandem with the observations on the effects of computer self-efficacy on motivation and integration of modern technologies in education (Paraskeva, Bouta and Papagianni, 2008), this hypothesis postulates that the constructor will correlate positively on perceived ease of use. This relationship is based on the lower-level identifiers of behavioural intention, which analyse the ability users have to undertake a course of action on the system to achieve a specific goal (Compeau and Higgins, 1995). Thus this hypothesis models the influence imparted on the students' perception on ease of technological operation (Moghadam and Bairamzadeh, 2009; Ariff *et al.*, 2012).

- ***H13: Technology anxiety will have a statistical positive influence on perceived ease of use.***

  Intrinsic to the design premise of the technology anxiety construct, is the determination of students' familiarity and comfort in engaging with technology through an inverted set of evaluative questions (Venkatesh *et al.*, 2003). To this end, this proposition reflects the correlation and effect imparted by technology anxiety on the students' perception of the technologies ease of use.

Furthermore, within the TAM4Edu model, hypotheses (*H14 - H17*) aim to identify the cross-over influence of determinants within the educational context developed. These relationships are described in the following hypotheses:

- ***H14: Social interaction will have a statistical positive influence with perceived enjoyment.***

  This hypothesis asserts that positive correlation is derived from the perception of technological enjoyment and the design for social interaction for socio-psychological aspects to learning. This relationship is based on the adoption of the theory of reasoned action in social contexts (Karahanna, Straub and Chervany, 1999), and emphasizes the importance of design considerations for the inclusion of social interaction, enhanced student motivation and hedonic reduction during student engagement and delivery of teaching and learning.

- ***H15: Perceived enjoyment will have a statistical positive influence with perceived lecture attention.***

  This proposition asserts that the intrinsic motivational factors imparted by enjoyment, are derived from interaction with educational technology which will impart a positive correlation to the student's attention to the lecture. The hypothesis aims to model the secondary effect of technological arousal and stimulation in accordance with the development of VARK modalities to positively impart influence between the determinants (Fleming and Baume, 2006; Wu, 2014).

- ***H16: Usability will have a statistical positive influence with perceived enjoyment.***

  This hypothesis is formulated on the secondary effects of usability design, imparted towards the perception of users through interaction and postulating that a positive correlation is imparted on students' enjoyment through the careful design of system usability in line with HCI guidelines (Shneiderman, 2010). From an educational perspective, the system's ability to intuitively embed conceptual understanding to users through interactive design, will contribute towards the enjoyment derived in active teaching and learning pedagogies.

- ***H17: Usability will have a statistical positive influence with technology anxiety.***

  Based on the intrinsic aim of usability heuristics to aid learnability and memorability of technological engagement (Preece, Rogers and Sharp, 2015), this hypothesis asserts a positive influence on the reduction of anxiety impediment perceived by students in using computer technology. In line with the observations noted by Olali (2014), the careful design of computer systems should impart factors of comfortable control and understanding of technology which reduce physiological barriers to user adoption (Lee and Coughlin, 2015).

Following the initial students' data collection through the construct questionnaire and analysis of the obtained results as described in section 6.2.2, the optimal selection of questions for each determinant, based on factor loading data were identified to provide TAM4Edu with an effective framework adoption. In line with the statistically determined items marked in

Table 6.7, 24 questions were implemented within the survey. As described in Table 6.8, these items solicit the students' acceptance of technology for each identified determinant within the proposed framework. Furthermore, following analysis of data variation within first-stage respondents, and in line with conclusions from recent literature on appropriateness and reliability of reference scales in TAM models (Ahmad and Ahlan, 2015; Idris, Mat Sin and Ya, 2015), a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) was adopted within the proposed framework. As shown within the Google Form survey designed in Appendix B.2, the order of questions was randomised with items marked with an *(R)* in Table 6.8 intentionally reverse coded to further expose potential unengaged student responses (Teo, 2009; Brezavšček, Šparl and Žnidaršič, 2014).

Table 6.8: Evaluation Questions adapted for each identified TAM4Edu determinant

Construct	Acronym		Evaluation Question
Perceived Usefulness	PU1		The technology used in this lecture helped me understand the subject effectively.
	PU2	(R)	I wasn't able to learn the subject effectively through the technology used.
	PU3		The lecturing technology used today enabled me to better understand abstract material.
Perceived Ease of Use	PEU1	(R)	The used technology was rather difficult to operate.
	PEU2		Performing tasks using the technology is intuitive
	PEU3		Overall, I find the technology easy to use
Behavioural Intention	BI1		I look forward to using the same technology again in the near future.
	BI2		The lecturing technology used in this lesson should be used regularly.
Computer Self-Efficacy	CSE1		I was able to finish the given task using the technology without supervision.
	CSE2	(R)	I needed someone to show me how the technology functions first.
Technology Anxiety	TANX1		Technology in general makes me nervous.
	TANX2	(R)	I felt comfortable using the educational technology.
Perceived Enjoyment	PENJ1	(R)	The used educational technology was boring.
	PENJ2		The actual process of using this lecturing technology was enjoyable.
Study Relevance	STREL1		I find the use of such technology as important in my studies.
	STREL2		Using the educational technology was relevant to my studies

Construct	Acronym	Evaluation Question
Usability	USE1	I find the information from the educational technology used to be very intuitive.
	USE2	Learning how to perform tasks using the technology was easy
	USE3	The feedback from interacting with the system was intuitive.
	USE4	Operating the educational technology was intuitive.
Social Interactivity	SOCINT1	The lecturing technology promoted discussion and collaboration with classmates.
	SOCINT2	The used technology permitted me to interact with my class mates.
Perceived Lecture Attention	PLA1	I felt very attentive during this lecture.
	PLA2	Through this lecture I would characterise myself as being concentrated.

**Evaluation questions marked in (R) are Reverse Coded*

6.3 Evaluation

Following the description of the deployed TAM4Edu evaluation methodology on educational technologies, this section details the data analysis that was undertaken to validate the model hypothesis defined in section 6.2.3. The gathered data was subsequently adopted to help differentiate the effectiveness of different educational technology, ultimately aiding in the investigation of assessing the suitability of the proposed tangible technology framework to facilitate the teaching and learning of abstract concepts.

6.3.1 Evaluation Methodology

The TAM4Edu was implemented for evaluation of educational technology used at Middlesex University Malta within undergraduate programmes in science and technology. A different set of participants were once more recruited on a voluntary basis and were asked to mark the questions written in English using a Likert scale. Participants took no longer than 12 minutes to complete the questionnaire. A total of 116 students from different disciplines of Computer Science, Business Information Systems and Computer Networks participated in the study. Based on the year of study, enrolled modules and the respective computing discipline, evaluation sessions were held in line with academic curricula to coincide with the delivery of abstract and complex concepts to students in each domain.

During each evaluation session, held in accordance with the methodology shown in Figure 6.7, the appropriate TUI framework and PC-based software were alternately utilised as the educational technology to explain identified threshold concepts. Participants were initially provided with a common introductory lecture on the abstract concept using conventional module slides, following which each class was randomly split into two quasi-equal control and experimental groups as illustrated from the demographic data of Figure 6.8(b). Each group of three (3) to four (4) students undertook a laboratory session in relation to the lecture delivery, and a set of predefined tasks were provided for simulation and experimentation using either a TUI framework or a control educational technology. After the completion of their laboratory exercise, students were supervised while compiling the online TAM4Edu questionnaire on their perceived personal experience of using the educational technology within their respective a priori session. This methodology provided a comparative evaluation on the suitability of the proposed TUI frameworks with respect to current educational technology adapted within HEI for teaching and learning computational science and technology concepts.

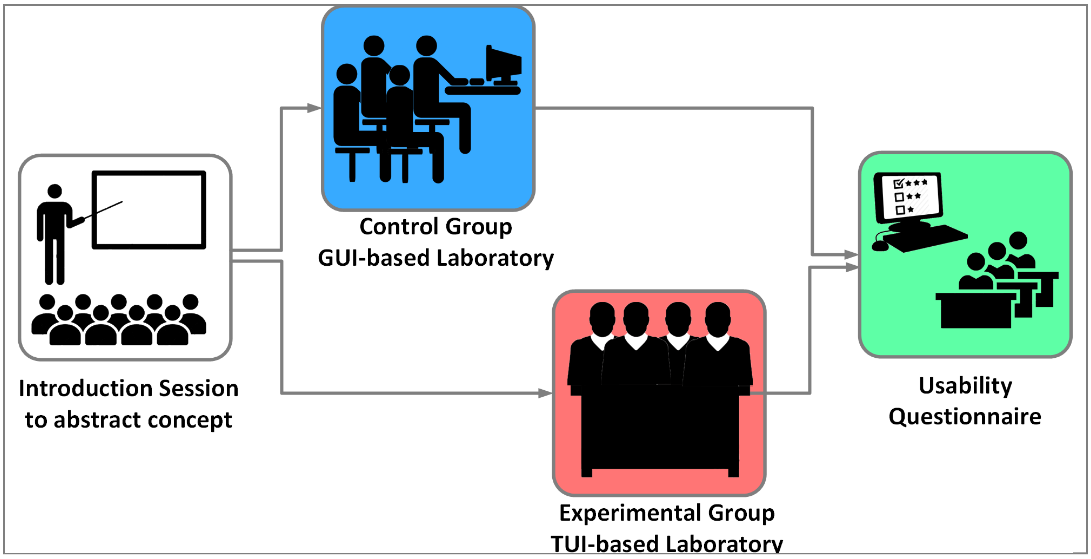


Figure 6.7: Evaluation methodology adopted for deploying TAM4Edu on educational technology.

The evaluation sessions were held on a variety of abstracted concepts within different university modules and thus participants ranged almost equally between second and third-year undergraduate students within each respective subject discipline as shown in Figure 6.8(c). The student age distribution histogram illustrates in Figure 6.8(a) the spread of students enrolled within modules in full-time and part-time modes of study with a median age of 21 years (mean = 22.8, σ = 5.1). The demographic gender data shown in Figure 6.8(d) characterises the characteristic enrolment of students at Middlesex University Malta and is in line with the skewness experienced within higher education institutions within the field of Science and Technology (Dečman, 2015; Fox, 2015) .

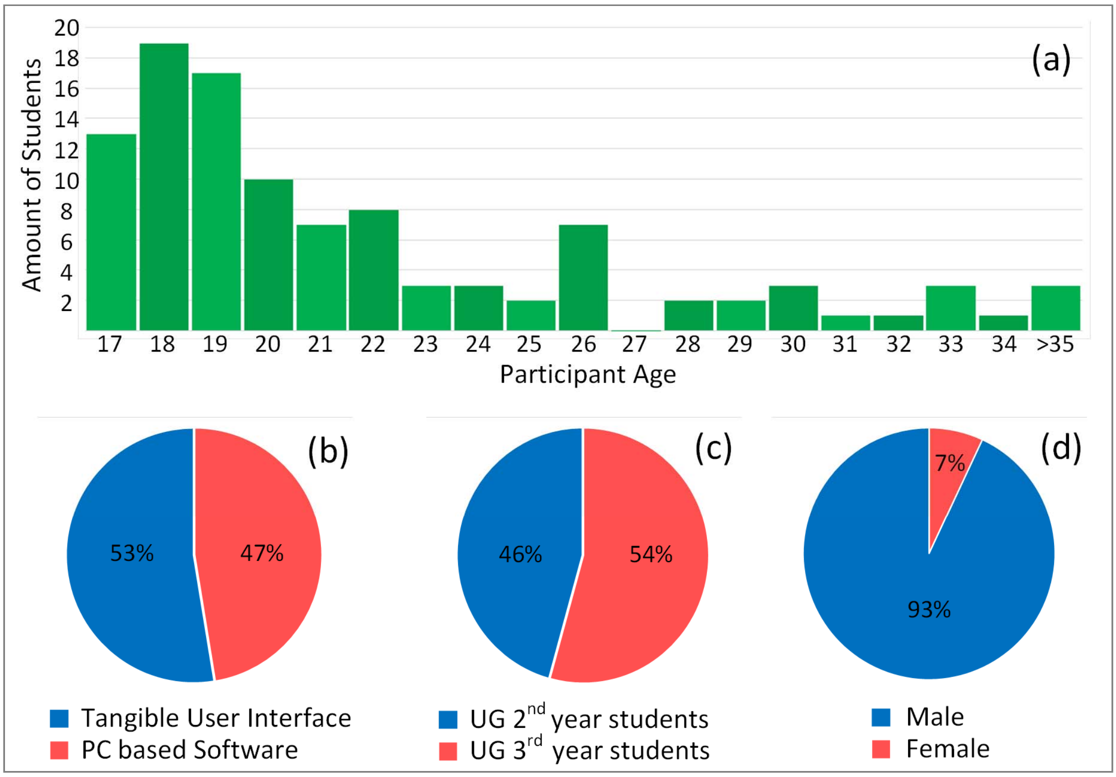


Figure 6.8: Socio-demographic student data showing:

a) Age distribution,

b) Educational technology evaluated,

c) Year of study distribution,

d) Gender distribution.

6.3.2 TAM4Edu validation

A similar data screening process was undertaken on the respondents' dataset to identify instances of unengaged or malicious responses. Making use of appropriately designed reverse-coded questions, lack of engagement was outlined on respondents that did not provide a suitable degree of variance ($\sigma < 0.5$) within their answers to the questionnaire (Lowry and Gaskin, 2014). Thus, by excluding these unnatural biases, the dataset was trimmed to a total of 105 entries. A descriptive analysis of the 5-point Likert responses showed that individual question scores ranged from 2.49 to 4.57 (mean=3.89, σ=0.35). This indicated a generally positive response to the framework questions with students' scores on construct items fairly distributed and varying significantly from the neutral value of 3.0 (Teo, 2016).

6.3.2.1 Determinant Correlation

To assess the hypotheses generated in subsection 6.2.3, a bivariate correlation of factors in the TAM4Edu model was analysed using aggregate scores on each determinant for a student population of 105. Based on the research questions to determine the influencing determinants of the TAM core model within educational technology, a two-tail person correlation was undertaken to examine the relationships between each factor at $\rho > 0.01$ as tabulated in the off-diagonal matrix in

Table 6.9.

Table 6.9: TAM4Edu factor correlation matrix (N=105)

	CSE	PENJ	PEU	PLA	PU	STREL	SOCINT	TANX	USE
Behavioural Intention (BI)	.275*	.665*	.643*	.776*	.688*	.603*	.532*	.521*	.683*
Computer Self-Efficacy (CSE)		.391*	.604*	.215*	.401*	.298*	.273*	.264*	.416*
Perceived Enjoyment (PENJ)			.656*	.663*	.755*	.610*	.608*	.527*	.709*
Perceived Ease of Use (PEU)				.646*	.729*	.577*	.504*	.613*	.778*
Perceived Lecture Attention (PLA)					.711*	.631*	.579*	.519*	.673*
Perceived Usefulness (PU)						.600*	.627*	.519*	.724*
Study Relevance (STREL)							.519*	.291*	.655*
Social Interactivity (SOCINT)								.508*	.590*
Technology Anxiety (TANX)									.597*
Usability (USE)									

The significant path coefficients in relation to the evaluated set of hypotheses, are further illustrated in Figure 6.9, which outlines correlations based on a Pearson $r(105) > 0.6$ (Ibrahim et al., 2018). In support of the architectural TAM relationships, hypothesis (H1 – H3) marked in red, exhibited a strong correlation in the TAM4Edu model confirming the appropriate embodiment of the underlying core TAM architecture. The obtained results further support the rejection of the null hypothesis on the positively influencing determinants for *Perceived Usefulness* (H4-H8) and *Perceived Ease of Use* (H9-13) as marked respectively in green and orange within Figure 6.9. Determinants such as *Perceived Enjoyment, Usability* and *Perceived Lecture Attention* provided strong correlation path coefficients to both PU and PEU acceptance factors, whilst the remaining constructs were able to explain influence on a unique factor as described within their respective hypothesis.

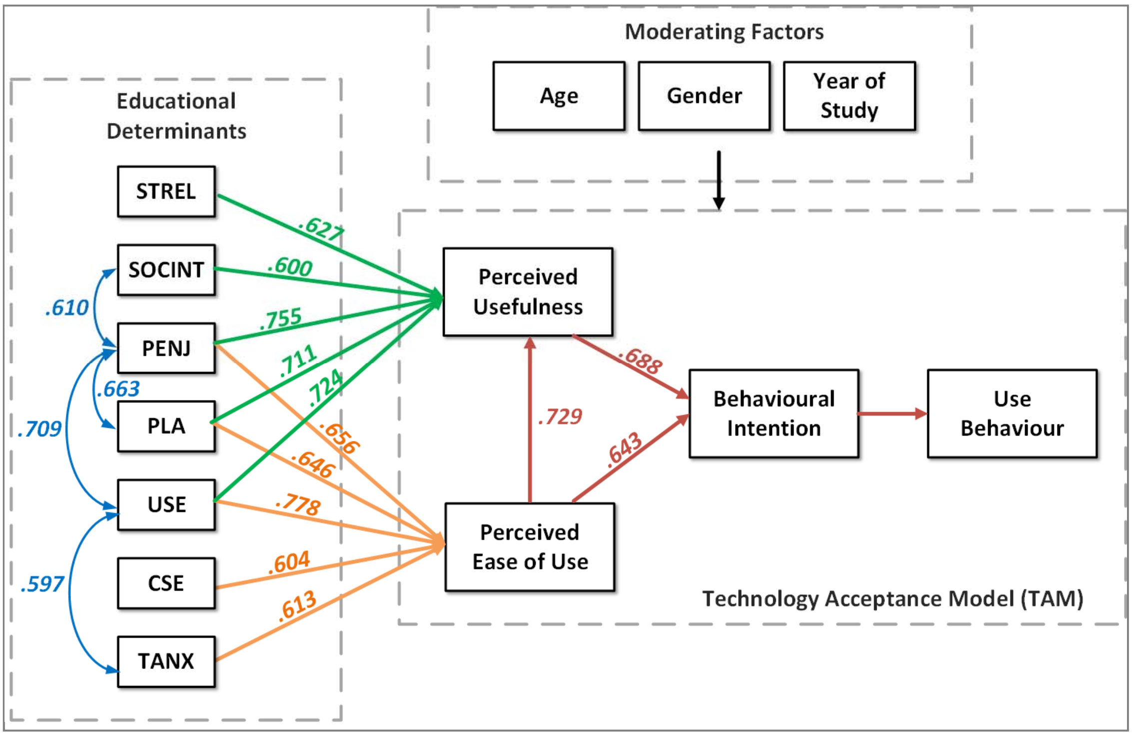


Figure 6.9: Path coefficients based on the TAM4Edu framework hypothesis for:

- *Technology Acceptance Modelling (red),*
- *Determinants of Perceived Usefulness (green),*
- *Determinants of Perceived Ease of Use (yellow),*
- *Intercorrelated dependencies between determinants (blue).*

The TAM4Edu model was further analysed using a linear regression analysis on each individual hypothesis as detailed in

Table 6.*10*. The R^2 value adjusted for population size, illustrates that each hypothesis is able to account for 35% to 60% (mean=44.3%, σ=7.62) of the variance exhibited on the respective dependent construct. The factor coefficient analysis additionally illustrates that all effects are statistically significant for each hypothesis at $\rho<0.01$. These results provided support for the determinants defined in the TAM4Edu model extension to describe the acceptance of educational technology.

*Table 6.*10: Linear regression analysis summary of TAM4Edu *hypotheses*

Hypothesis Summary					Coefficients				
	DV	IV	R	R Square	Factor	B	Beta	t	Sig.
HI	BI	PU	.688	.468	Constant	1.095			
					PU	.733	.688	9.62	.000
H2	BI	PEU	.643	.408	Constant	1.235			
					PEU	.703	.643	8.53	.000
H3	PU	PEU	.729	.527	Constant	1.031			
					PEU	.748	.729	10.82	.000
H4	PU	STREL	.627	.387	Constant	1.047			
					STREL	.722	.627	8.17	.000
H5	PU	SOCINT	.600	.360	Constant	1.943			
					SOCINT	.528	.600	7.61	.000
H6	PU	PENJ	.755	.566	Constant	.960			
					PENJ	.734	.755	11.69	.000
H7	PU	PLA	.711	.500	Constant	1.137			
					PLA	.727	.711	10.25	.000
H8	PU	USE	.724	.519	Constant	1.276			
					USE	.706	.724	10.64	.000
H9	PEU	PENJ	.656	.425	Constant	1.397			
					PENJ	.622	.656	8.83	.000
H10	PEU	PLA	.646	.412	Constant	1.434			
					PLA	.645	.646	8.60	.000
H11	PEU	USE	.778	.601	Constant	1.118			
					USE	.741	.778	12.56	.000
H12	PEU	CSE	.604	.364	Constant	1.823			
					CSE	.565	.604	7.67	.000
H13	PEU	TANX	.613	.369	Constant	.749			
					TANX	.751	.613	7.87	.000
H14	PENJ	SOCINT	.610	.366	Constant	1.995			
					SOCINT	.552	.610	7.81	.000
H15	PENJ	PLA	.663	.435	Constant	1.396			
					PLA	.698	.663	8.99	.000
H16	USE	PENJ	.709	.498	Constant	1.401			
					PENJ	.712	.709	10.20	.000
H17	USE	TANX	.597	.350	Constant	2.512			
					TANX	.464	.597	7.54	.000

Note: DV = dependent variable; IV = independent variable; R = correlation coefficient; R square = percentage of variation in DV, explained by IV; B = unstandardized coefficient used to predict DV, Constant = intercept (c); Beta = standardized coefficient and the relative size of the influence of a variable; Sig. = indicates if null hypothesis can be rejected or not.

Analysis on the intercorrelation between determinants hypotheses, outlined in blue within Figure 6.9, showed a strong correlation for hypothesis (H14-H16), whilst H17 had a moderate-strong borderline correlation of $r(105) = 0.597$ as highlighted in

Table 6.*10*. The anomaly observed in this intercorrelation is further substantiated by the relatively high level of kurtosis observed in the *TANX* determinant at 4.059. Deeper inspection of the results outlined that the scores for this determinant were aggregated tightly around a high central rating of 4.3 (σ = 0.68), thus indicating that the evaluated participants had very little apprehension towards technology, a factor explained through the demographic moderating data, since all participants in the study were reading ICT or engineering undergraduate degrees at university level. Consequently, the influence of usability albeit significant for user adoption of technology was not able to significantly influence the high degree of familiarity with technology already ingrained in the participating students.

Extended analysis of the factor loading between the proposed determinants for the TAM4Edu framework, further outlines an additional set of intercorrelations between constructs in complement to the defined hypothesis. As illustrated in Figure 6.10, the determinant of *usability* held statistical correlation to both *perceived lecture attention* and *social interaction*. These observations endorse the importance of pedagogical support within system design for aiding lecture attention (Berry, 2008), together with critical requirements of educational technology to meet the flexibility and social interaction needs of a collaborative teaching and learning environment (Shiratuddin and Landoni, 2002; Kreijns, Kirschner and Jochems, 2003). In addition, the statistical influence of *social interaction* with *perceived lecture attention* within TAM4Edu supports the assertion of collaborative learning through technology to present a more effective educational environment for students (Resta and Laferrière, 2007).

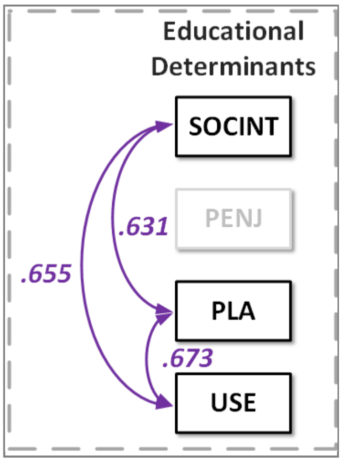


Figure 6.10: Visualisation of additional intercorrelations observed between TAM4Edu determinants.

6.3.2.2 Multivariate Regression Analysis

In evaluating the appropriateness of the adapted TAM4Edu architecture, illustrated in Figure 4, a Multivariate Regression Analysis (MRA) was adopted on each model's dependent determinants; PU and PEU (Rhodes, 2012). The independent constructs described within TAM4Edu, were analysed using a stepwise MRA for a statistical significance level of 95% for their ability to describe the core constructs of the proposed educational technology acceptance model.

In examining determinants for the *Perceived Usefulness* construct, the multiple regression models tabulated in

Table 6.11, identified four predictors that could provide a unique, statistically significant prediction of the dependent PU at a multiple R(4) correlation of 0.844. The variability of PU could further be accounted for by an adjusted R^2 of 70%. The Durbin-Watson test on this regression confirmed at 1.8 that no serial correlation exists between the independent TAM4Edu determinants. An Analysis of Variance test (ANOVA) further outlined, at a statistical significance of $\rho<0.001$ that the explanatory power of the regressed model is well described at $F(4) = 61.67$, $df = 100$.

Table 6.11: Stepwise multiple regression model on perceived usefulness

Model	Variables Entered	R	R Square	Adjusted R Square	Std. Error of the Estimate	ANOVA F	Sig.
1	PENJ	.755	.570	.566	.572	136.54	.000
2	PEU	.816	.666	.659	.507	101.68	.000
3	PLA	.835	.697	.688	.485	77.60	.000
4	STREL	.844	.712	.700	.476	61.67	.000

The factor loading analysis of the regressed model is described in Table 6.12. The positive standardised β coefficients support the hypothesised positive influence of the proposed TAM4Edu determinants on the PU construct. The model data illustrates that each component provides a significant standardised loading to the determinant factor and all the constructs are statistically significant at $\rho<0.05$. The collinearity tolerance values highlight that within the selected independent variables, each construct has a unique prediction of at least 42.4% on PEU variance and thus the regressed model, depicted in Figure 6.11, does not exhibit any statistical multicollinearity between constructs.

Table 6.12: Multivariate regression model on perceived usefulness

Factor	Standardized Coefficients	t	Sig.	Collinearity Tolerance
Intercept		-.418	.677	
PENJ	.320	3.883	.000	.424
PEU	.303	3.942	.000	.487
PLA	.211	2.641	.010	.451
STREL	.157	2.213	.029	.572

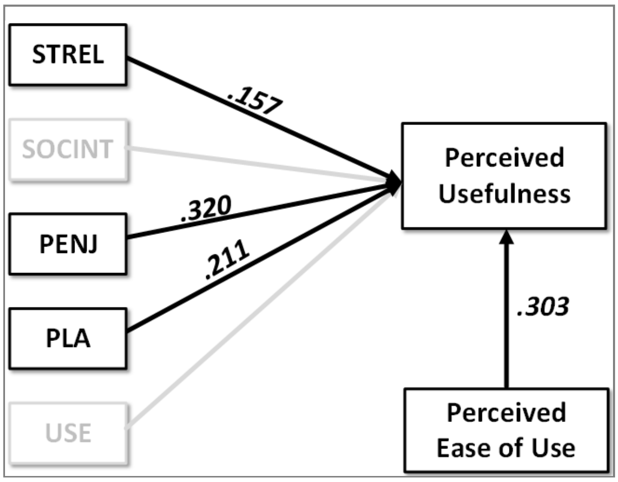


Figure 6.11: Regressive model for the determinant of perceived usefulness in TAM4Edu.

An MRA computed on the mediating determinant of *Perceived Ease of Use,* similarly derived four uniquely significant predictors to model the influence of the dependent variable PEU at a multiple R(4) correlation of 0.837, as tabulated in Table 6.13. As described within this data, accounting for variability and sample size, the adjusted R^2 model exhibits factor prediction at 68.9%. Following confirmation of no serial intercorrelation between identified PEU determinants at a Durbin-Watson test value of 1.95, an ANOVA analysis was undertaken on the PEU regressed model. This analysis confirmed the explanatory power of the PEU regression at $F(4) = 58.5$, $df = 100$ at a statistical significance of $\rho<0.001$.

Table 6.13: Stepwise multiple regression model on perceived ease of use.

Model	Variables Entered	R	R Square	Adjusted R Square	Std. Error of the Estimate	ANOVA F	Sig.
1	USE	.778	.605	.601	.535	157.77	.000
2	CSE	.803	.645	.638	.510	92.55	.000
3	PLA	.824	.679	.670	.487	71.29	.000
4	TANX	.837	.701	.689	.473	58.55	.000

Validating further the TAM4Edu hypothesis (H9 – H13) on the positive influence by external determinants on the PEU construct, the factor loading analysis outlines positive β coefficients for the regressed model as detailed in Table 6.14. As outlined from these results, the standardised loading of each component on the PEU determinant model, illustrated in Figure 6.12, is statistically significant at $\rho<0.01$. Furthermore, as shown in Table 6.14, the model does not embody multicollinearity effects between constructs, with each determinant providing a prediction effect on PEU variance which is at least 41.1% unique.

Table 6.14: Multivariate regression model on perceived ease of use.

Factor	Standardized Coefficients	t	Sig.	Collinearity Tolerance
Intercept		-.141	.888	
USE	.427	5.007	.000	.411
CSE	.232	3.838	.000	.818
PLA	.212	2.789	.006	.520
TANX	.187	2.685	.008	.618

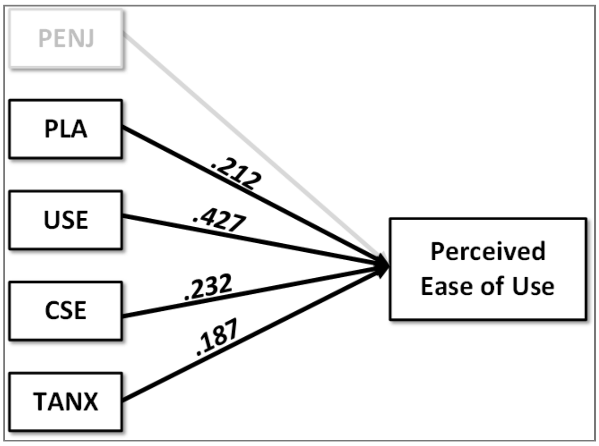


Figure 6.12: Regressive model for the determinant of perceived ease of use in TAM4Edu.

6.3.3 Analysis of TUI acceptance

In accordance with the evaluation methodology described in section 6.3.1, participants were independently exposed to two different educational technologies within their laboratory sessions with quasi-equal sample distribution as illustrated in Figure 6.8(b). The TAM4Edu evaluation data was thus split between both groups to evaluate the students' perceived differences in the adoption and use of TUI technology with respect to conventional PC based software. To this effect, this evaluation answers the suitability aspect of the research question by analysing the students' perceived ease of use and perceived usefulness in using TUI to explain abstract concepts within an HEI setting.

6.3.3.1 Multivariate Analysis

As to protect the analysis from a type 1 analysis error in providing a 'false positive' result in focused comparisons, the segregated data between both groups was analysed for statistical significance using a one-way multivariate analysis of variance (MANOVA) (Cramer and Bock, 1966). The test was undertaken on all the TAM4Edu determinants using a trimmed dataset of 105 participants as described in section 6.3.2, distributed in a ratio of 52 TUI and 53 PC based software evaluations. Thus, to test the hypothesis that there will be one or more mean differences between educational technologies (TUI, PC), the multivariate analysis was undertaken using a Pillal's Trace which provides robustness towards the violations of the assumption of equality of the covariance matrix on the model's determinants across groups (Kres, 1983). As detailed in Table 6.15, a statistically significant MANOVA effect was obtained, Pillai's Trace = .285, $F(10,94) = 3.75$, $\rho < 0.001$. This result rejects the null hypothesis and outlines that there is a significant difference on the TAM4Edu perceived determinants between the groups evaluating the different educational technologies used. The partial $\eta^2 = .285$ further outlines the multivariate effect size of the model's determinants, on the educational technology perceived differences, by implying that 28.5% of the variance in the canonically derived model is accounted for by the analysis.

Table 6.15: MANOVA Pillai's trace test on TAM4Edu determinants across educational technology evaluation groups

Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Observed Power
.285	3.754	10	94	.000	.285	.993

Prior to conducting a series of follow-up ANOVAs on the independent determinants, the homogeneity of variance assumption was tested by examining the standard deviations between groups. This revealed that the largest standard deviations were less than four times the size of the corresponding smallest deviation, thus validating the robustness of the ANOVA analysis (Howell, 1992). As highlighted in

Table 6.16, all determinants of the TAM4Edu model, with the exception of *TANX* and *CSE,* were statistically significant. These marginal outliers illustrate that in line with the demographic moderating data, the participating HEI students who were all enrolled in undergraduate ICT or engineering degrees, showed little apprehensive difference within their scores on *technology anxiety* and perceived *computer self-efficacy* when asked to use and evaluate either technology. Conversely, the effect sizes of the significant determinants within the TAM4Edu model were ranged between .082 (*STREL*) to .194 (*PENJ*) at greater than 85% (median = 99.7%) observed power.

Table 6.16: ANOVA analysis on the between-subject effects of the TAM4Edu determinants

Factor	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
BI	17.231	1,103	17.231	24.683	.000	.193	.998
PEU	11.990	1,103	11.990	19.716	.000	.161	.993
PU	13.831	1,103	13.831	22.048	.000	.176	.996
STREL	4.865	1,103	4.865	9.222	.003	.082	.853
SOCINT	18.785	1,103	18.785	23.422	.000	.185	.998
PENJ	16.130	1,103	16.130	24.822	.000	.194	.999
PLA	14.080	1,103	14.080	23.820	.000	.188	.998
USE	14.684	1,103	14.684	22.362	.000	.178	.997
CSE	3.487	1,103	3.487	3.775	.055	.035	.486
TANX	1.442	1,103	1.442	3.075	.082	.029	.412

6.3.3.1 Determinant Analysis

In light of these positive analysis results, the estimated marginal mean scores on each TAM4Edu determinant were computed as tabulated in Table 6.17. As visualised through the histograms of Figure 6.13, the usage of TUI as an educational technology imparted a higher evaluation rating with respect to traditional PC based software on all the determinants of the TAM4Edu framework.

Table 6.17: Marginal mean scores between educational technologies on TAM4Edu determinants

Factor	Educational Technology	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
BI	Tangible User Interface	4.44	0.12	4.21	4.67
	PC Based Software	3.63	0.11	3.40	3.86
PEU	Tangible User Interface	3.32	0.13	3.05	3.58
	PC Based Software	2.95	0.13	2.69	3.21
PU	Tangible User Interface	4.55	0.11	4.33	4.77
	PC Based Software	3.76	0.11	3.54	3.98
STREL	Tangible User Interface	4.32	0.11	4.11	4.54
	PC Based Software	3.65	0.11	3.43	3.86
SOCINT	Tangible User Interface	4.32	0.11	4.11	4.53
	PC Based Software	3.58	0.11	3.38	3.79
PENJ	Tangible User Interface	4.37	0.11	4.16	4.59
	PC Based Software	3.65	0.11	3.43	3.86
PLA	Tangible User Interface	4.34	0.12	4.09	4.58
	PC Based Software	3.49	0.12	3.25	3.73
USE	Tangible User Interface	4.32	0.10	4.12	4.52
	PC Based Software	3.89	0.10	3.69	4.08
CSE	Tangible User Interface	4.42	0.09	4.23	4.61
	PC Based Software	4.19	0.09	4.00	4.38
TANX	Tangible User Interface	4.24	0.11	4.02	4.47
	PC Based Software	3.49	0.11	3.27	3.72

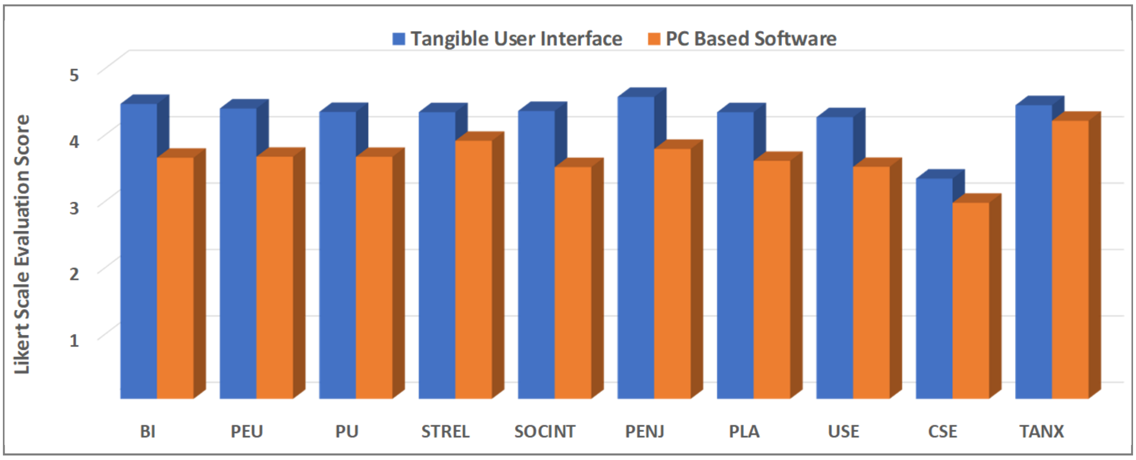


Figure 6.13 Comparative mean assessment ratings on TAM4Edu determinants between educational technologies.

An independent sample t-test was undertaken on the TAM4Edu output determinant, to analyse the effective *behavioural intention* of students to use either technology within their educational pursuit. The analysis confirmed, at $t(df=103) = 4.98$, that TUI technology obtained an average higher rating of 0.81 (σ: 0.16) in comparison to PC based software by students when these technologies were adopted within higher educational contexts to aid in active teaching and learning pedagogies. This result was achieved at a statistical significance of $\rho<0.001$ and analysed under Levene's test affirmation for homogeneity of population variance. This significant result outlines the fact that the proposed TUI frameworks are better perceived by students with higher technological acceptance and intention to use, than the conventionally employed laboratory sessions undertaken through current PC based software. This outcome was further assessed through the mediating core determinants of the TAM4Edu framework, shown in Table 6.18, whereby statistical significant result differences, $\rho<0.001$, were obtained for PU and PEU in favour of TUI implementations. The results in Table 6.18 further outline that the TUI registered a mean difference of around 15% improvements on these core determinants, highlighting a better suitability of tangible technology at explaining abstract concepts.

Table 6.18: Independent sample t-test on perceived differences between technologies of the TAM4Edu fundamental determinants.

Constructor	t	df	Mean Difference	Std. Error Difference	Mean Difference (%)	Sig. (2-tailed)
Behavioural intention (BI)	4.968	103	0.81	0.16	16%	0.000
Perceived Ease of Use (PEU)	4.440	103	0.68	0.15	15%	0.000
Perceived Usefulness (PU)	4.695	103	0.73	0.15	14%	0.000

Following the positive results obtained in the acceptance of educational TUI technology in HEI, a more detailed analysis was undertaken on the external constructs of the model which, as analysed within TAM4Edu, provide a factorial loading on the student's perceptions of technology on both a personal level and the students' perspective regarding the system. This served to provide a contextual understanding of the design considerations that impacted on the *perceived usefulness* and *perceived ease of use* determinants of the developed TUI frameworks. Thus, the external constructors' scores obtained following the experimental TUI technology were compared to conventional PC based software as a control, as illustrated in Figure 6.14.

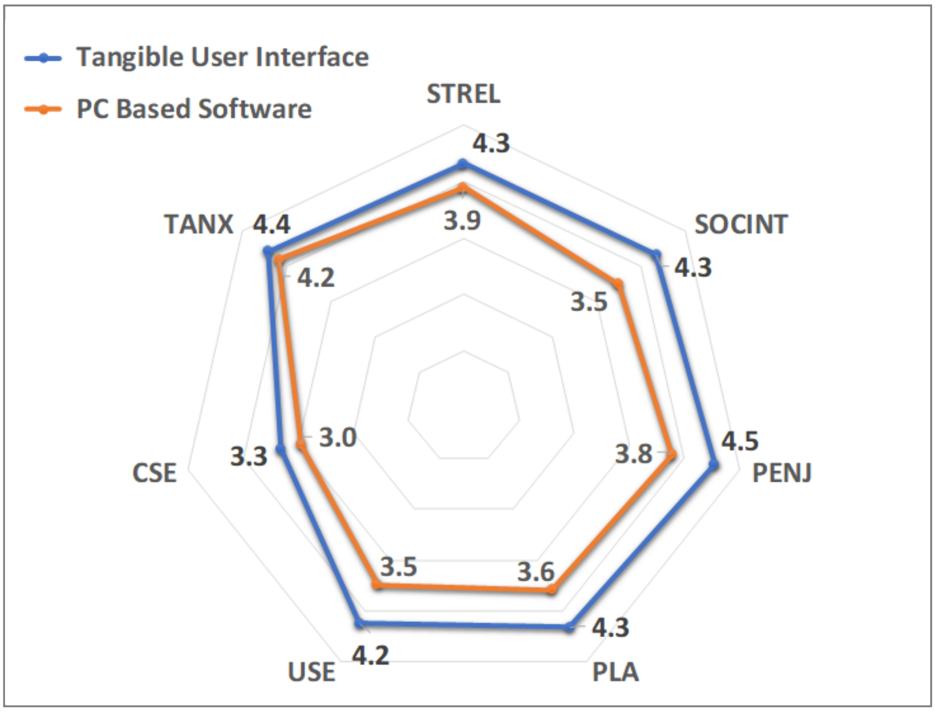


Figure 6.14: Comparative mean radial plot of TAM4Edu external determinants on TUI and PC based educational technology.

The largest improvement of the proposed TUI technology was registered on the high-level identifying determinants of the TAM4Edu model, where statistical significance at $\rho<0.01$ was observed for the improvements on factors such as; *SOCINT* ($\mu = 0.85$, $\sigma = 0.17$), *PENJ* ($\mu = 0.78$ $\sigma = 0.16$) and *PLA* ($\mu = 0.73$, $\sigma = 0.15$). The 19%-22% increase in rating provided by students on these determinants, illustrates that the intrinsic interlacing of digital and physical interactions afforded through TUI technology augmented the students' *perceived enjoyment* and *perceived lecture attention* by 21% and 20%

respectively. These significant enhancements attest further to the capabilities of designed tangible frameworks to aid in developing active learning pedagogies, which increase student attention, enjoyment and social interaction through the interactive educational processes. These opportunities are intrinsically augmented within tangible architectures which eliminate the physical and interactive burdens associated with PC-based technology in providing an enriched learning environment. Moreover, the statistically significant increase in *study relevance -STREL* ($\mu = 0.43$, $\sigma = 0.14$) further indicates the capacity of TUI frameworks to provide a deeper understanding and learning of abstract and complex concepts.

With respect to lower-level identifying constructors on technology efficacy, a statistically significant difference was observed on the *usability* of TUI with a mean improvement of 21% on the determinant *USE* ($\mu = 0.75$, $\sigma = 0.16$) at $\rho<0.01$. This factor increase, highlights the enhanced usability aspects of efficacy, utility, learnability and memorability, that were effectively exploited by the developed TUI frameworks within an educational perspective. This success was also reflected in the factors of *technology anxiety* and *computer self-efficacy*, which as highlighted in Table 6.15 do not present a statistically significant difference of means variance between both student groups. This reflects that the perception of these determinants on TUI systems, is relatively similar to PC-based software, to which participants are very familiar as detailed from the demographic profile analysis.

A holistic perspective of imparted capabilities by the evaluated educational technologies to effectively engage users in adopting and using technology within their studies, was observed from Figure 6.14. An aggregate analysis of the external determinants, displayed in Figure 6.15, shows that the perceived score on the TAM4Edu external determinants for TUI is of 4.2 ($\sigma = 0.4$) with respect to PC based software which students rated at 3.6 ($\sigma = 0.7$). The observed overall difference of 16% in enhanced suitability and effectiveness from adopting TUI technology in HEI, was further analysed using an independent sample t-test which provided a statistical significant result at $t(df=103) = 5.22$, $\rho<0.001$. The higher score for TUI with respect to the PC-based control, thus, attests to the intrinsic pedagogical and system design characteristics imparted within the developed tangible technology. Consequently, these results affirm the suitabilty of adopting TUI frameworks to aid in the effective teaching and learning of abstract computational science and technology-based concepts within HEI contexts.

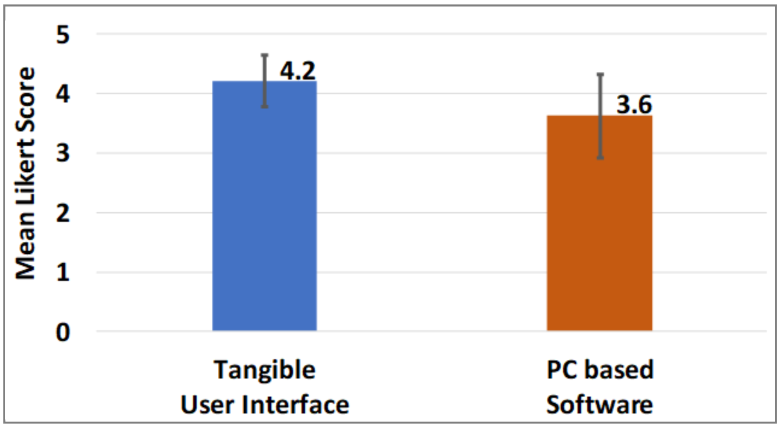


Figure 6.15 Student perceived Likert score aggregates on the TAM4Edu explanatory external dependents for evaluated educational technologies.

Chapter 7
Evaluating the Effectiveness and Suitability of Tangible Technology for Highly Abstract Concepts

In light of the empirical results obtained within this research, this chapter presents a pedagogical review on TUI, which frames the work undertaken in critically discussing the design considerations for implementation of tangible technology in abstract concepts. The analysis resonates with the observations outlined in TUI taxonomies for the need tangible frameworks to provide empirical guidance for TUI system designers (Shaer and Hornecker, 2009; Schneider, 2017), whilst addressing the gap between technological development, practical demonstrations and pedagogical theory (Price *et al.*, 2009; Martinez-Maldonado, 2017). In a reflective review, this chapter critiques the pedagogical affordances of TUI for deployment in teaching and learning abstract concepts commonly present within higher education.

To this end, section 7.1 discusses the potential of the developed TUI frameworks to effectively aid in teaching and learning through an analysis of pedagogical theories in relation to tangible interfaces. In tandem with literature analysing the inherent attributes of TUI to support learning activities through various modalities and learning strategies, the review outlines the lack of empirically evaluated pedagogical frameworks for abstracted concepts (Antle *et al.*, 2013). Section 7.2 describes a reflective evaluation undertaken for the threshold concepts identified in chapter 6, to derive a set of descriptors for abstract and complex notions. The knowledge gap on TUI design frameworks is investigated further in section 7.3.1 , where a reflective evaluation is undertaken on the capacity of the proposed frameworks to effectively aid in the education of abstract concepts in HEIs. At the confluence of this analysis and the obtained results, section 7.3.2 proposes a set of design guidelines, for the development of TUI frameworks as an educational technology, described based on pedagogical theories and empirically evaluated TUI frameworks.

7.1 Pedagogical Considerations in TUI Design Elements for Teaching and Learning.

As detailed in the review of chapter 2, various research has outlined the intrinsic capabilities of TUI systems to provide an accessible interaction which promotes hands-on engagement and allows for exploration, discovery and reflection on educational concepts possibly through collaborative learning (C. O'Malley and Fraser, 2004; Fernaeus and Tholander, 2006; Price *et al.*, 2009; Schubert, 2016; Devi and Deb, 2017). However, empirical work that provides evidence for these claims in view of augmented pedagogy is scarce (Bakker and Niemantsverdriet, 2016), and research has mostly focused on technical development and creation of descriptive taxonomies (Holmquist, Redström and Ljungstrand, 1999; Ullmer and Ishii, 2001; Fishkin, 2004; Zuckerman, Arida and Resnick, 2005; Shaer and Hornecker, 2009; Zuckerman, 2015). Whilst the latter can inform design by sensitizing concepts and heuristics, they do not provide explanatory accounts for TUI pedagogical considerations. Alas, efforts to create TUI-based learning experiences have often focused solely on technology, ignoring the critical and interdependent design of the learning activities (Antle and Wise, 2013).

With the exception of limited research on TUIs deployed in primary education (Chipman *et al.*, 2006; Zufferey *et al.*, 2009; Marshall, Cheng and Luckin, 2010; Horn, Crouser and Bers, 2012; Fan *et al.*, 2014; Schneider, 2017), TUI research has mostly relied on intuition when designing physical interactions, an approach criticized for potentially leading to incorrect design assumptions (Edge and Blackwell, 2006). Furthermore, the lack of pedagogical considerations has led considerable research to be anecdotal in nature (Klahr, Triona and Williams, 2007; Antle, Droumeva and Corness, 2008) and provided mixed results when deploying TUIs in conceptually complex and abstracted notions (Shaer *et al.*, 2010; Schneider and Blikstein, 2015; Arif *et al.*, 2016).

Initial work to provide a pedagogical perspective was undertaken by Dourish (2001), who introduced the notion of embodied interaction through the task-focused activities with concrete materials. Albeit the work outlines the need for effective learning to engage in both task-focused activity and objective reflection through tangible technology, lack of detail is provided on the affordances of interaction on the educational domain. The primary conceptual overview of educational and psychological learning theories towards tangible learning, was provided by Claire O'Malley and Fraser (2004). This work, however, whilst proposing a structured descriptive framework did not provide the specified level of detail needed to inform TUI design decisions. In contrast, the study by Edge and Blackwell (2006) explicate a design framework on children's TUI programming environments but alas, their work focuses more on design representation as opposed to learning.

Marshall (2007) delineated six perspectives for tangible learning, defining broad pedagogical categories including; *possible learning benefits, integration of representations, concreteness and sensory directness* and *effects of physicality*. Although foundational for identifying gaps in knowledge and expanding on the sensitized concepts of tangible learning defined by Hornecker and Buur (2006), this framework eschewed from providing design guidance on TUI development. Price *et al* (2008) presented a taxonomy for conceptualising tangible learning environments by analysing the influence on cognition through different couplings between digital information and physical artefacts. Yet whilst providing illustrative empirical research for their category descriptors, their framework provides minor design guidance and focuses only on one of the several pedagogical dimensions imparted by TUI learning.

This aspect was expanded in the most recent literature within the area, whereby Antle and Wise (Antle and Wise, 2013) built upon prior work to describe further areas of cognitive development including; *embodied interaction, symbolic reasoning, information processing* and *distributed cognition* (Antle, 2007). The proposed *Tangible Learning Design Framework*, however, was derived from theoretical guidance through evaluation of literature (Stolterman and Wiberg, 2010), and lacked an empirical evaluation on the proposed explanatory guidelines (Antle and Wise, 2013). Moreover, similar to a priori frameworks (Marshall, 2007; Price *et al.*, 2008), this research was focused on children's pedagogical learning in primary education and thus did not consider the capacity and challenges associated with TUI design for complex and abstracted concepts in HEI.

In light of the surprisingly uncommon work within this area, this section systematically evaluates the proposed TUI frameworks through a review of different teaching and learning pedagogical theories exploited through TUI architectures. In tandem with observations and assertions in established theoretical literature, this chapter presents a systematic pedagogical analysis of the developed design contributions in an evaluative review of the TUI frameworks introduced in HEI for teaching and learning highly abstract concepts.

7.1.1 Constructivist learning

The foundational model of constructivism postulates that through technology the development of mental models is undertaken by learners as they express and reflect on concretized and explicit knowledge (Papert, 1983). In view of Mellar and Bliss (1994), exploratory and expressive aspects within constructive pedagogy, tangible user interfaces support expressive learning by enabling the construction of physical representations through the creation of novel media (Price *et al.*, 2008). Within complex concepts, the designed TUI frameworks integrated these pedagogical capacities by providing students with the capabilities of developing several exploratory topologies through active manipulation of tangible representations. In frameworks such as *Computer Network Protocols* (section 5.2) and *Robotic Operating System* (section 5.9), the tangible interaction was designed to allow for the exploration and expression of combinatorial architectures in respective domains beyond what is feasibly possible in practical media. Furthermore, the enriched visual and haptic feedback designed within TUI architectures, enabled students to understand the models by manipulating casual relations simulated in conceptually complex theories. Thus, through a learning process of discovery (De Jong and Van Joolingen, 1998), students are able to intuitively experiment within the designed dynamic models with greater cognitive attention provided to the underlying conceptual mechanisms.

In contexts such as *Database Normalisation Processes* (section 5.3), the tangible framework provides a controlled setting to gradually introduce progressively complex conceptual structures through isolated models. This design methodology embodies the constructivist pedagogy of scaffold learning derived by Wood *et al* (1976). Whilst various research has provided theoretical support towards this learning style for reducing teaching complexity in primary education (Rosenshine and Meister, 1992; van de Pol, Volman and Beishuizen, 2010), the designed frameworks embody these principles within tangible interaction on progressively complex and abstracted notions in HEI. Thus by enabling tiered presentation of increasingly complex scenarios, *Database Normalisation Processes* and *Queuing Theory Computation* (section 5.4) frameworks enable students to conceptualise their understanding through a designed dynamic reduction in degrees of interactive freedom to promote learning activities linked to ‘*sequencing*’ (King and Just, 1991; Andrews and Halford, 2002) and ‘*chunking*’ (Halford, Wilson and Phillips, 2010) strategies (McCredden *et al.*, 2016).

7.1.2 Cognitive learning

Based on the human cognitive architecture proposed by Atkinson and Shriffin (1968), the theory postulates that students master scientific concepts by building flexible and runnable mental models through active stages of learning and reasoning within working memory (Redish, 1994; Cowan, 2014). The developed TUI architectures, such as *Artificial Neural Networks* (section 5.8) and *Multi-threaded Task Scheduling* (section 5.5), provide direct provision to this pursuit through computational offloading (Zhang and Norman, 1994). In these frameworks, problem-solving and learning are directly supported by external representations of the designed scenario, thus facilitating the objective reflection and effort needed to interrogate and reconstruct cognitive models in rectifying conflicting beliefs (Scaife and Rogers, 1996; Kim and Maher, 2008). Furthermore, through the interactive visuospatial feedback designed within these tangible frameworks, students are able to engage in self-dialogue on their externalised conceptual understanding providing a ‘*backtalk’* learning dimension within their engagement (Schön, 1987).

Cognitive learning is sponsored further within the proposed TUI frameworks by bolstering the learning strategy of ‘*Complementary Actions’* (van Gelder and Clark, 1998). This active learning pedagogy denotes a strategy whereby learners toggle between either e*pistemic actions;* to manipulate/organise or encode the environment around them to facilitate their task-solving process, or *pragmatic actions* which bring the users directly closer to their reaching their physical goal (Fjeld and Barendregt, 2009). The *Search-Space Problems* framework (section 5.5) endorses these complementary actions whereby students are able to undertake a broader analysis of the problem solution space, by manipulating the physical position of tangibles prior to engaging in pragmatic discovery of identified solutions. The effectiveness of this strategy in aiding the problem-solving capacity of complex scenarios resonates with the observations undertaken in puzzle-solving effectiveness and efficiency with children when comparing either TUI or GUI based jigsaw puzzle pieces (Antle, Droumeva and Ha, 2009; Goldin-Meadow, 2014). In tandem, the tangible objects and design within *Search-Space Problems* assisted students by diminishing the complexity of their search-space, without requiring explicit logic deduction, hence supporting cognitive theories of *perceptual intelligence* and *conceptual inference* (Scaife and Rogers, 1996; Hutchins and Palen, 1997).

Pedagogical studies emphasize the need to understand the nature of technological impact on the finite cognitive capacity of learners (Baddeley, 2003), outlining the difference between ‘*germane’* demands that contribute to learning and ‘*extraneous*’ cognitive loads that distract from it (Kirschner, 2002; Baddeley, 2017). The intrinsic design and use of physical manipulatives, aid in reducing the latter loading effects by providing students with a heightened sense of intuitiveness and interaction capacity through the psychomotor domain (Gagné R, 1970). Moreover, the *extraneous* load was further reduced within frameworks for *Queuing Theory Computation* and *Object-Oriented Programming* (section 5.7) where TUI systems were designed coherently with informational relations that mirror those familiar to HEI students in the real world - thus demanding less cognitive processes for contextual mapping. This provided the proposed TUI frameworks with the potential to free up more cognitive resources that could be devoted towards conceptual learning, based on parallel observations undertaken by Marco et al (2009) on kindergarten children.

7.1.3 Embodied Cognition

The coherent mappings designed in the TUI frameworks between input actions and system responses referred to as stimulus-response compatibility in ergonomics literature (Wickens and Hollands, 2000), interlinks another pedagogical aspect to teaching and learning through the process of embodied cognition. Spanning the domains of cognitive science, linguistics and philosophy, this implicit pedagogical affordance was defined for TUI by Dourish (2001) as phenomena, “that by their very nature occur in real time and space”. Through design, TUI interactions allow for a seamless combination of various embodied interactions on different symbolic levels as they intrinsically bridge between physical and digital divides (Bürdek, 2005; Antle, Corness and Droumeva, 2009). To this end, frameworks such as *Computer Network Protocols* and *Database Normalisation Processes* tightly coupled tangible objects with enhanced digital information as to natively embody abstracted attributes onto physical constructors. In line with previous observations on primary education (Sapounidis and Demetriadis, 2013), this strategy effectively aids in the iconic representation of abstracted concepts for delivery by allowing students to additionally leverage on symbolic learning within their cognitive study.

This cognitive process was further aided in the proposed TUI frameworks through the conscious design of image schemas, which via recurring patterns of visual and haptic experience help develop abstract mental structures (Johnson, 1987). Integrating the use of familiar input gestures on tangible manipulatives, the designed TUI architectures allow users to interact unconsciously with the system, thus diverting their perceptive focus on learning, rather than operating the system. In addition, the designed associative and proprioception actions for students' interaction through physical movement, further aid to cement the learners' underlying representational understanding through kinaesthetic learning activities (Klemmer, Hartmann and Takayama, 2006; Holland *et al.*, 2011).

The integration of active tangibles within *Artificial Neural Networks* and *Robotic Operating System* frameworks further extends the embedded capabilities of the proposed frameworks. Within these implementations, the tabletop TUI frameworks assume benefits commonly associated with *Kinetic Memory* or *Constructivist Assembly* platforms (section 4.1), by integrating physical objects with electronic embedded controllers (Terrenghi *et al.*, 2005). Using a variety of sensors and actuating components, these active manipulatives afford a richer paradigm to users which enable the representation of highly complex concepts by intrinsically extending the user's embodied and interactive domain.

7.1.4 Collaborative learning

As a consequence of the intrinsic conceptual externalisation process embedded within tangible interaction, TUI systems provide a liberal platform for the pedagogical design of distributed cognition. This pedagogy interrelates the outcomes of the individual with those of the group, and defines the provision of a natural learning context where knowledge is co-constructed, shared and socially negotiated (Vygotsky, 1978). In contrast with PC-based technology, tangible architectures provide a shared space for socio-cultural transactions, whereby users can monitor each other's gaze more easily when undertaking distributed interaction (Suzuki and Kato, 1993). The tabletop architecture designed in chapter 4 purposely integrates these pedagogical requirements to provide an effective TUI interactive system, capable of achieving these collaborative learning goals in HEI contexts with larger student cohorts when contrasted to current TUI architectures in the literature.

The passive tracking of physical manipulatives in tangible architectures, provides further avenues for pedagogical engagement, whereby through concurrent interaction, students can partake in collaborative interaction on systems with distributed shared control (Zuckerman, Arida and Resnick, 2005; Barneva *et al.*, 2018). This phenomenon was well observed In *Search-Space Problems* and *Robotic Operating System* TUI frameworks, whereby the concept's complexity was distributed to group members who negotiated their conceptual understanding mediated by simultaneous tangible interactions. Furthermore, psychological research outlined secondary benefits to social collaborative learning, where participants increase their awareness of other members' activity, encourage situated learning and better communicate their current state of work (Fernaeus and Tholander, 2006; Klemmer, Hartmann and Takayama, 2006).These outcomes were reflected in the empirical evaluation of TUI frameworks within higher education whereby these observations were noted through both subjective and objective evaluation metrics as reported in the previous chapters.

7.1.5 Learning Modalities

Within the last few decades, '*learning styles*' have become a highly influential area of interest (Pashler *et al.*, 2008; Wu, 2014) comprised of a large body of research, investigating the manner in which different learning methodologies influence individuals' capabilities to capture, process, understand and integrate information (Kolb, 1984; Coffield *et al.*, 2004; Truong, 2016). This pedagogy integrates personality indicators such as; the *Myers-Briggs Type Indicato*r (Myers and Briggs, 1962), to categorize the effects of different type of learners' personalities in acquiring and integrating information (Cassidy, 2004).

Prominent within the field of educational technology, the *Visual, Aural, Read/Write, Kinaesthetic (VARK)* model, proposed by Fleming and Mills (1992), has received sustained observations for providing an enhanced pedagogical experience and increased student satisfaction with learning (Drago and Wagner, 2004; Eom, Ashill and Wen, 2006). Through stimulating different sensory modalities in accordance with students' individual preferences for learning (Fleming and Baume, 2006), TUI systems provide a natural ability to integrate a haptic interaction element within their architectures, complimenting further the technologically traditional visual and technologic modalities (Manches and O'Malley, 2012; Schweppe and Rummer, 2014).

As observed within the proposed TUI frameworks and the TAM4Edu evaluation model (chapter 6), student engagement and *perceived lecture attention* were both positively correlated with introducing a multitude of information modalities for conceptual and cognitive processing. The simultaneous engagement of these senses was designed in several combinations in these frameworks further extending the capacity of different interaction modalities. Whilst in *Database Normalisation Processes*, audio guidance complimented visual and haptic cues, the active tangible elements in *Artificial Neural Networks* and *Robotic Operating System* introduced coherent feedback by complimenting real-time user feedback with additional visual and vibrational output through manipulatives, stimulating further aspects of the VARK interactive modalities.

7.2 Abstract Concepts in Higher Education

Scientific domains often challenge learners with comprehending abstract and multidimensional phenomena in their curricula (Dede *et al.*, 1999), difficulties which increase further within concepts learnt at higher education. These conceptual predicaments further entail the need to relate several informational units simultaneously within a mental relational structure, for new concepts to be fully conceived (Maybery, Bain and Halford, 1986; Halford *et al.*, 2012). Thus, Science, Technology, Engineering and Mathematics (STEM) students often need to understand concepts composed of multiple processes containing several components, which interact with one another at various levels (Chi, 2005; Azevedo *et al.*, 2011). Furthermore, many abstract concepts are relational concepts; that are characterized by their links to other external concepts rather than by their own intrinsic properties or internal structure (Markman and Stilwell, 2001). Cowan (2014) argued that, whilst new STEM material posits relational complexity which is regularly overwhelming for students (Hay, Kinchin and Lygo-Baker, 2008), the complexity of the conceptual integration process is fundamental to learning.

Within their nature, abstract concepts involve qualitatively different types of attributes than concrete concepts and commonly anchor representation for a generic scenarios rather than relatable contextual situations and properties (Borghi *et al.*, 2017). Thus, students' lack of real-life referents for intangible phenomena, coupled with an inability to perceptualize abstract models, presents significant hurdles for STEM educators in HEI settings to apply this theory within teaching situations (Hayes and Kraemer, 2017). Moreover, these complex concepts, while seeming basic and trivial to expert academics, commonly involve the difficult and effortful integration of many interrelated components for novices (Larkin *et al.*, 1980).

Grounded within the theory of relational complexity of concepts in learning (Halford, 1982), the pedagogical notion of '*Threshold Concepts'* characterises these difficulties when teaching and learning a core abstract concept within a subject (Tight, 2014). Centred around the evolved models by Meyer and Land (2003, 2005, 2006; 2008), threshold concepts are defined through the following characteristics;

- **Transformative –** Once understood, a threshold concept imparts an ontological and conceptual shift in the perception of a subject or part thereof.
- **Irreversible –** The change of perspective acquired through an understanding of a threshold concept is unlikely to be forgotten and considerable effort is required to unlearn. This aspect reflects one of the challenges experienced by expert practitioners in going back to understand the difficulty experienced from the students' perspective.
- **Integrative –** The understanding of a threshold concept exposes hidden interrelations to other concepts/knowledge. This aspect pertains to the relational integration of component concepts, and thus relational complexity underpins a fundamental role in explaining the difficulty of threshold concepts (McCredden *et al.*, 2016).
- **Bounded –** The conceptual space of understanding, borders terminal frontiers with thresholds in other conceptual domains of knowledge.
- **Troublesome Knowledge –** Based on Perkin's (1999) definition, threshold concepts entail inert and alien knowledge that impart counterintuitive or complex understanding to previous misconceptions/limitations within learner's knowledge.

7.2.1 Evaluation Methodology

Underpinned by the knowledge extracted from the literature, a two-stage evaluative reflection with domain practitioners was conducted on the HEI threshold concepts identified within chapter 5. A qualitative evaluation methodology, as depicted in Figure 7.1, was undertaken with academic experts in the field of computational science and technology at Middlesex University. Through a structured interview and review process in line with their respective area-of-expertise and academic research, participants were asked to define and elaborate on the characteristics of specific threshold concepts encountered within their respective curricula. By means of an open discussion, participating experts enlisted a set of reflections defining aspects of abstraction and complexity that constitute the threshold concept within tuition. At least three academic practitioners who are actively engaged in lecturing or research within each of the identified threshold concepts were selected for this study, and individually evaluated for knowledge elicitation.

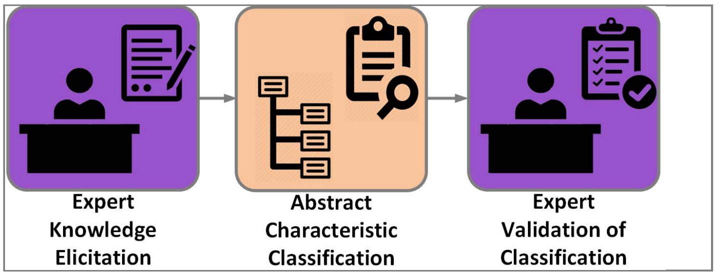


Figure 7.1 Evaluation Methodology adopted to derive abstract and complex descriptors of identified threshold concepts.

7.2.2 Abstract and Complex Descriptors

Peculiar to typical characteristics of abstract concepts, each threshold concept is embedded in mental processes or emotions that specify relevant situational aspects (Wiemer-Hastings and Xu, 2005). Thus, to provide a set of relatable factors across each concept within the domains of computational science and technology, developed in chapter 5, a set of abstract descriptors were composed as detailed in Table 7.1. This descriptor set aggregately reflected the identified conceptual aspects across all domains, whilst removing contextual annotations.

Table 7.1: Definitions for abstract or complex concept descriptors

Abstract or Complex Concept Descriptors	Definition
Curriculum threshold concept	The lack of profound understanding of the concept presents a barrier to the ability to perceive and interpret additional knowledge within the domain.
Transformative perspective	Conceptual understanding imparts a transformative shift in thinking, which is drastically different from a priori knowledge or methodologies
Interdependency between entities	Concepts contain a high degree of relational complexity between numerous components which impart a direct influence on the conceptual outcome
Input data sensitivity	This aspect relates to the complexity of relationships within the conceptual model and describes the concept characteristic of exhibiting cascade or recursive effects to change on input data.
Hidden computational entities	Abstract concepts involve hidden internal processes which influence data through mathematical or logical computations throughout execution.
Unbounded entity configurations	The applicability of an abstract concept entails an unbounded possibility of topological or configurational possibilities.
Dynamic conceptual stages	Abstract concepts are composed of variate conceptual stages within which instruction sets and functional operations differ. The internal conceptual processes of a stage further provide a complex relational effect on the dynamic functionality of subsequent computations.
Time-variant entity processes	The output characteristics of a complex concept are governed by the behavioural change in time, which dynamically influence the information or conceptual execution.
Distributed data dependencies	The conceptual output solution is aggregately dependent on the concurrent information and state of various internal data entities.
Multiple output solutions	Abstract concepts allow for the possible derivation of multiple valid output solutions towards a unique problem.
Integrated functional processes	The concept’s outcome is derived from the integrated operation of numerous internal conceptual processes and entities.

Abstract or Complex Concept Descriptors	Definition
Theoretically focused	Abstract concepts are highly theoretical and challenging to contextualise and apply to problem-solving instances
Unrelatable internal entities	Intangible phenomena in abstract concepts lack real-life practical referents for contextualising functional understanding
Contextually dependent processes	Abstract concepts present decision-making processes which are contextually dependent on the application domain.

As illustrated in Figure 7.1 the second round of evaluation was subsequently performed in an individualistic manner with each domain expert reviewing the validity of the defined descriptors. During the latter, each academic further refined their a priori analysis of the respective threshold concepts attributes and classified their assessments accordingly with respect to defined descriptors. This ensured the semantic suitability of the classification descriptors to reflect the complexity and abstracted properties expressed for each unique concept.

The results for each threshold concept from respective domain experts were subsequently aggregated in Table 7.2. As visualised within this table, a three-valued metric was adopted to reflect expert assessments, differentiating occurrences of unanimous agreement on the applicability of a descriptor, from instances in which academics provided conflicting but equally plausible conclusions. Visually illustrating a holistic and comparative analysis of the developed TUI frameworks within this research, the evaluated data in Table 7.2 outlines the fact that identified concepts for TUI development, generally present characteristics of threshold concepts within HEI curricula. These results attest to the overall ability of the proposed TUI frameworks to curtail the barriers experienced in threshold concept understanding within higher education tuition.

Furthermore, Table 6.2 enables the identification and suitability assessment of TUI technology to aid in the various distinct aspects of teaching and learning complex and abstract concepts. In tandem with the evaluation results undertaken within chapter 5 and chapter 6 on the effectiveness and suitability of TUI in educational deployment, the conceptual descriptor mapping in Table 7.2 provides an analytical assessment of the capacity and capability of the proposed educational frameworks. Thus, this analysis outlines the ability of aptly designed TUI frameworks to successfully adopt the distinctive and compound aspects of abstract and complex concepts within tangible user interaction paradigms.

Table 7.2: Comparative analysis of conceptual descriptors within threshold concepts implemented in TUI frameworks

Abstract or Complex Concept Descriptors	Proposed TUI Frameworks							
	Computer Network Protocols	Database Normalisation Processes	Queuing Theory Computation	Multi-threaded Task Scheduling	Search-Space Problems	Object-Oriented Programming	Artificial Neural Networks	Robot Operating System
Curriculum threshold concept	✓	✓	~	✓	✓	✓	✓	✓
Transformative perspective	~	✓	✓	✓	✓	✓	~	✓
Interdependency between entities	✓	~	✓	✓	✓	✓	✓	✓
Input data sensitivity	✓	✗	✓	✗	✓	✗	✓	✓
Hidden computational entities	✓	✗	✓	✓	✗	✗	✓	~
Unbounded entity configurations	✓	✓	✓	✓	✓	✓	✓	✓
Dynamic conceptual stages	✓	✓	✗	~	✗	~	~	~
Time-variant entity processes	✓	✓	~	✗	✗	✗	✗	✓
Distributed data dependencies	~	✓	✓	✓	✓	~	✓	~
Multiple output solutions	✗	~	✓	✓	✓	✓	~	✗
Integrated functional processes	✓	✓	✓	✓	✓	✓	✓	✓
Theoretically focused	~	✓	✓	~	✓	✓	✓	✓
Unrelatable internal entities	✗	~	✗	✓	✗	~	✓	✗
Contextually dependent processes	✗	✓	✗	✗	✓	~	✗	~

Table legend: ✓ - Unanimous agreement, ~ - plausible alternatives, ✗ - unanimous disagreement.

7.3 Design Guidelines on TUI Technology for Abstract Concepts

This section evaluates the suitability and effectiveness of adopting TUI frameworks for abstract concepts in higher education through the confluence of pedagogical and STEM concept research undertaken within this chapter. Following a critical review of limited literature contributions for educational TUI design guidelines in section 7.3.1, this section outlines a set of design considerations aimed at aiding the development of TUI systems within HEI contexts. Thus, based on the derived descriptors for abstract and complex concepts, a set of TUI design guidelines is defined in section 7.3.2, which through the pedagogical and technological aspects, evaluate the design considerations undertaken within the developed TUI frameworks. The guideline applicability on interrelated design elements is subsequently detailed in section 7.3.3 providing an understanding of the instances of application during educational TUI design.

7.3.1 TUI design models

Pedagogical theorists and learning designers commonly argue with substantial precedent on the value of applying multiple theories, in a reasoned way, to inform learning design principles in educational technology (Wiley, 2002; Smith and Ragan, 2005; Cronjé, 2006; Beetham and Sharpe, 2013). Thus, literature models advance the notion that the various learning styles and theories emphasise different yet interdependent levels of scale in active learning pedagogy and hence a holistic perspective is essential for effective educational technology design (Wilson and Myers, 2000; Conole *et al.*, 2004; Koehler *et al.*, 2014; Ary *et al.*, 2018).

In light of the limited research and literature available on frameworks providing design guidance for developing TUI systems (Mazalek and van den Hoven, 2009; Shaer and Hornecker, 2009), this section addresses the critiqued limitations of current pedagogical TUI design frameworks reviewed in section 7.1. To this end, an empirically evaluated explanatory framework was compiled within this study, in line with the collective call for research advancements and identified limitations in current TUI guidance frameworks (Marshall, 2007; Antle and Wise, 2013).

Accordingly, the proposed design guidelines were developed through a dialectic process of analysis, reflection and critique from different research perspectives on TUI technology, pedagogical theories and abstract concept descriptors. Moreover, furthering the sensitized concepts, design considerations and heuristics in descriptive tangible framework literature (Ishii, 1998; Shaer *et al.*, 2004; Rogers and Muller, 2006; Antle, 2007; Price *et al.*, 2008), the explanatory guideline framework provides an analytical, prescriptive and generative understanding on the manner in which TUI design considerations explicate relations between learning constructs. Hence, the proposed design guidelines extend the theoretical evaluations adopted currently in descriptive framework literature to inform TUI development through a reflective review of supported empirical evaluation and experiential scholarship derived from the design of educational TUI frameworks.

In contrast to interaction design frameworks which aim to deliver desired user experiences (Preece, Rogers and Sharp, 2015), the educational design guidelines described in this section embrace a wider perspective, by establishing the design for a tangible learning environment in line with desired learning experiences that support pedagogical processes. Thus, through the interwoven design considerations of learning tools, materials, procedures, and tasks, the proposed guidelines illustrate the TUI design considerations for the combined and effective enactment of desired learning experiences, to support and facilitate the active learning of threshold concepts.

Furthermore, in contrast to previous literature on TUI design frameworks which confined tangible pedagogical description towards educating children in early stage learning (Price *et al.*, 2008; Antle and Wise, 2013), this section extends a set of TUI design guidelines for development and implementation of tangible technology in HEI. More specifically, the guidelines derived from this study address the compounded challenges faced in higher education by defining design considerations aimed to encapsulate abstract and complex conceptual aspects.

7.3.2 TUI design guidelines

Therefore, in line with the descriptors defined in section 7.2.2, the proposed guidelines provide a technical and practical perspective on design and development considerations for TUI frameworks, by integrating the experiential knowledge and empirical results obtained within this study. These outcomes are closely supported through the practical exemplification of design decisions, undertaken in chapter 5. To this end, the empirical adaption of TUI frameworks with respect to the variant descriptors defining abstract and complex attributes in HEI educational concepts, is described in the context of learning design and pedagogical considerations.

- ***Concept Descriptor 1:*** *Transformative perspective.*

  TUI Design Guideline: *Development of interactive tiered interfaces.*

  The design of dynamic tangible interactive setups provides TUI frameworks with the ability to support the transformative understanding needed for threshold concepts through constructivist learning processes such as scaffolded learning. In the latter, students can progressively construct more complex scenarios at their own pace, supporting the individualistic capabilities of students to undertake and transform from their a priori knowledge. Moreover, this transformative process is aided from a cognitive learning perspective through the provision of reflective design stages following interaction which provides students with the ability to engage in self-dialogue on the conceptual understanding. These stages are further facilitated through the tangible design for embodied cognition whereby students are provided interwoven visual and haptic feedback along different learning modalities to pedagogically support their learning.

As exemplified in the *Object-Oriented Programming* framework (section 5.7), the TUI was designed to provide a tiered presentation and introduction to the different concepts within the object-oriented paradigm. The sequential progression from *abstract class design* to *instantiation* stages, enabled students to conceptualise their understanding through 'sequencing' and 'chunking' strategies associated with scaffolded learning. The dynamic interactive design of the TUI setup allows students to freely configure more elaborate solutions through the introduction of additional *attribute* tangibles, thus embedding a constructivist approach within the educational TUI system. Aiding the transformative understanding of object-oriented programming, students are provided with dynamic visual animations linking different attributes within designed abstract classes. Furthermore, through the timely haptic feedback on tangibles through physical rotation and illumination, the tangible technology supports the process of reflective thinking on the conceptual aspects using different modalities. The introduction of graphical and code-based explanations further aids to reduce the cognitive load experienced by students in understanding the abstracted effects of their design, thus generating a facilitated environment where students can undertake a transformative shift in their understanding.

- ***Concept Descriptor 2:*** *Interdependency between entities.*

  TUI Design Guideline: *Embodiment of icon representations and associative patterns.*

The extended interaction domain afforded by TUI frameworks presents a compelling opportunity to aid in explaining and exemplifying the relational complexity held within threshold concepts. By embedding the use of multiple VARK modalities in the iconic representation of tangibles, students are able to bridge the complexity and abstractness of entity relations through cognitive theories of perceptual intelligence and conceptual inference. Furthermore, through the design of image schemas and recurring visual and haptic patterns, TUI frameworks provide a facilitating environment for students to develop abstract mental structures on the entity interdependency influences through cognitive computational offloading.

The TUI framework for *Search-Space Problems* (section 5.5) exemplified the complexity reduction of entity interdependencies, through the careful design of tangible and digital interfaces. The selection and design of physical manipulatives provided students with the ability to undertake conceptual inference between different entities. By use of tangible accessories such as '*oars*', and through the different base designs of each manipulative, perceptual intelligence was stimulated in students to facilitate the relationship and the contextualisation of entity attributes in the river crossing scenario. Moreover, through the use of physical and digital artistic schemas, interdependencies between entities were further elucidated through coherent colour and graphical representations throughout the *state-space search*, *river-crossing simulation* and *tangible objects* – all of which are design aspects within the TUI framework. The use of dynamic visualisations, animations and interaction guidance, further allows the *Search-Space Problems* framework to facilitate the interpretation of entity dependencies by students, through the embodied cognition of symbolic images and illuminated effects to assess the validity and effectiveness of the undertaken state-space search.

- ***Concept Descriptor 3:*** *Input data sensitivity.*

  TUI Design Guideline: *Integration of information through tight physical and digital coupling.*

  By interweaving the physical and digital domains in perceptual and computational coupling, tabletop TUI systems provide an extended environment to capture the cascade and recursive effects exhibited by concepts in response to input data. Through the design of augmented constructive models, students are enabled to interactively manipulate and pedagogically explore different system alternatives in a collaborative manner. Coupling constructivist and collaborative learning to aid cognitive understanding, TUI frameworks thus provide the opportunity for students to visualise and interact with relationally complex concepts through actively controlled computational simulations. This afforded teaching modality, allows tangible educational technology to facilitate the understanding of the exhibited underlying effects on the conceptual models from diversified configuration parameters.

  These pedagogical aspects are reflected in the TUI framework implementation for *Artificial Neural Networks* (section 5.8), whereby the relational complexities of *input*, *hidden* and *output nodes* on different parameter values, were exemplified within a *back propagation neural network* topology. Through distributed control and interaction of individual entities, students are able to collaboratively construct increasingly complex ANN models and interactively design different configuration parameters. The computational and perceptual coupling designed within the framework, further provide an intuitive design and control environment – this diverted students' perceptual and cognitive load towards understanding the recursive effects exhibited by the network nodes on fluctuations of configured input and *synaptic weightings* within the simulation's convergence process.

- ***Concept Descriptor 4:*** *Hidden computational entities.*

  TUI Design Guideline: *Utilisation of active tangibles for computational representation.*

  In extending the interactive paradigm beyond traditional educational technology, TUI architectures provide students with the ability to express and interact with abstract and hidden entities through an enriched environment. Aiding the expressive learning in constructivist and embodied learning pedagogies, TUI systems equip students with iconic tangible manipulatives, which provide the ability to concretize abstracted notions. Architecturally, the intrinsic spatial and computational aspects in TUI frameworks also provide an embedded context for supporting cognitive epistemic actions in organising and encoding sets of abstract and hidden computational entities. In addition, through the design integration of computational and perceptual feedback on active tangibles in educational TUI frameworks, students are able to interact with abstract computational functions. These manipulations are further mapped on visual representations that provide the ability to conjure up logical and arithmetic results through coherently interlaced digital and tangible outputs.

  Within the *Artificial Neural Network* framework, this abstract concept descriptor was embedded through the design of tangible entities in the iconic representation of computational entities within the network. Abstracted concepts such as hidden nodes, were further developed through active *cloud* tangibles which embodied a distinctive visual and illuminated colour scheme, to represent different computational dependencies between entities. This provided the TUI frameworks the capacity to conceptualize the arithmetic functions and results of *hidden nodes* and *synapses* through dynamic VARK modalities of text and animated graphics enriched with kinetic and responsive tangible actions within manipulatives. Furthermore, the active paradigm extended through the TUI framework provided students the ability to interact with virtual or hidden computational entities through the use of functional or value adjustments of synapses and nodes, through physical manipulation of the *weight* tangible - which enabled real-time cognitive interaction and understanding of underlying computations.

- ***Concept Descriptor 5:*** *Unbounded entity configurations.*
  TUI Design Guideline: *Provision for constructive interactive topologies.*

  The implementation of TUI design decisions in system purpose and domain interaction, provide tangible technology with the ability to accommodate and alleviate this complexity descriptor. In line with constructivist pedagogy, students are provided with an unbounded exploratory interface through the proposed TUI tabletop architecture (chapter 4) whereby, together with collaborative design and socially distributed interaction, TUI frameworks allow the expressive development and investigation of indeterminate entity topologies and configurations. The embodied cognition and perceptual intelligence affordances designed on physical tangibles, further aid students in reducing their cognitive load through the ability to explicate mappings and information through the physical and digital construction of topologies. This externalisation capability provides students with the ability to focus on the casual relations defined within the concept, whilst facilitating the cognitive load needed to visualise and construct runnable mental models in working memory.

  The TUI design proposed for *Computer Network Protocols* (section 5.2) allows students to scaffold their constructive learning through an unbounded interactive interface upon which topological configurations are tangibly setup and manipulated. This provides students with the ability to progressively include more complex network designs involving *additional routers* and topological connections. Through the embodied interactive design of symbolic and familiar tangibles, students are able to engage in interactive interactions such as proxemics, translations or rotational manipulations using physical objects. The former allowed students to connect and dynamically alter the topology of the network, whilst the designed rotational manipulations enabled the custom configuration of entities such as *cable media bandwidth* and/or *router settings* in line with unbounded desired scenarios. Furthermore, the *Computer Network Protocols* TUI framework, affords students the ability to externalise a designed topological network through physical models. This insight is further perceptually coupled with graphically displayed configurational information for each defined entity. Collectively, this design provided the designed TUI framework with the ability to engage students in pedagogical activities of distributed cognition on the functionality of the protocol, and to entice collaborative negotiation on their conceptual design and understanding of different configurations.

- ***Concept Descriptor 6:*** *Dynamic conceptual stages.*

  TUI Design Guideline: *Design of interactive segmentation.*

The dynamic coupling between physical manipulatives and digital computation, provides TUI frameworks with a unique ability to alter the representation and functional aspects of implementation through different stages of execution. This intrinsic attribute provides TUI frameworks the capability to anatomize abstract and complex concepts within a scaffolded learning pedagogy, whereby distinct yet dependent isolated conceptual models are '*chunked*' and '*sequenced*'. By means of this design approach, TUI systems present a dynamic reduction in a concept's degrees of freedom, thus breaking down the abstract and relational cognitive complexity into less overwhelming, staged instruction models. This pedagogy further allows students to actively control their learning advancement through interactive manipulation and thus individually govern their learning progress according to their rate of internalising conceptual understanding. In addition, by integrating different interactive VARK modalities, TUI frameworks provide the opportunity to design and expose students towards different functional and instruction processes on conceptual entities at different stages of execution.

As exemplified in the *Database Normalisation Processes* framework (section 5.3), students engaged sequentially in the construction, conceptual understanding and progression of the distinct normalisation stages throughout their learning activities. Whilst tightly embodying tangible objects with *dataset information*, the framework presents students separate instruction sets and functional requirements on *dataset* entities illustrating and teaching different conceptual methodologies in a scaffolding approach. Through the use of graphical animations, instructional audio, kinetic interaction and digital data visualisation, the TUI framework amalgamates different interactive modalities to guide students in understanding the dynamic instructions and relational dependencies at each normalisation stage. These modalities were further designed through a coherent schema of digital and physical representation, which reduced the extraneous cognitive load imparted on students in apprehending the interaction required at each operational stage and conversely leads to direct cognitive focus on conceptual learning.

- ***Concept Descriptor 7:*** *Time-variant entity processes.*

  TUI Design Guideline: *Reactive design for real-time data sensing through active manipulatives.*

  Through the design of tangible interaction, TUI frameworks provide an intrinsic capability to infer and interact with the behavioural entity and process changes throughout the execution of an educational simulation. Through computational coupling, TUI design considerations provide the opportunity for students to interactively explore the time-variant behavioural functionalities of entities, in line with constructive learning pedagogies for cognitive model development. Moreover, through the seamless integration of physical and digital interactive paradigms in the design and use of active tangible entities, TUI frameworks are able to coherently map time-variant responses to interactive entity stimuli. Thus, the apt design of TUI educational technology, provides the ability to design coherent information relations mirroring real-world interaction, thus reducing cognitive load resources expended on contextual mapping.

Through the TUI framework design for teaching and learning *Robotic Operating System* (section 5.9), the constructivist freedom imparted in topology design and configuration, allows students to explore various permutations of the functionality of entities during the conceptual execution of the operating system processes. Thus, by dynamically altering the state of nodes between *subscribers* or *publishers*, students can appreciate the variance imparted along the relational dependencies of entities, and hence cogitate on the reactive conceptual processes. The active tangibles designed within the *Robotic Operating System* TUI framework further extend the tangible interaction capabilities through the integration of *operational sensor nodes*. These entities, whilst sensitive to environmental interaction, provide students with the ability to physically manipulate their environment and observe the computationally coupled effects of *fused sensor data* through the reactive framework. Whilst presenting an intuitive and perceptive interactive paradigm to students through familiar electronic components, the TUI framework allows the simulation and understanding of time-variant processes elicited through different *data fusion* and *node configuration* processes.

- ***Concept Descriptor 8:*** *Distributed data dependencies.*

  TUI Design Guideline: *Support for concurrent interaction through distributed entities.*

  Through the design of concurrent interaction, TUI frameworks provide a natural pedagogical affordance towards collaborative learning through co-constructed and distributed tangible interaction. This design provides the ability to delegate conceptual entities between group members, invoking the need to collaboratively negotiate the system understanding. From a cognitive perspective, this tangible interaction design provides students with the ability to toggle between '*complimentary actions*' states; *epistemic actions* in organising and configuring data in distributed entities, and *pragmatic* discovery in understanding collaboratively designed solutions.

  The interactive design within the *Queuing Theory Computation* framework (section 5.4), illustrates the capacity for TUI technology to embody distributed entities with strong relational dependencies in epitomizing the algorithmic simulations of mathematical queue modelling. Additionally, through the supportive design for collaborative interaction, the deployment of spatially distributed computational entities enables students to collaboratively design and configure entities simultaneously whilst engaged in discussion over the parameter effects. Moreover, from a cognitive perspective, the interactive design of the developed *Queuing Theory Computation* framework, also enabled students to engage in *complementary actions* for learning. *Epistemic* learning opportunities are afforded through the tangible design and configuration of a queueing environment with distributed entities and relations. Subsequently, *pragmatic actions* enable students to alter mathematical models for *Poisson distributions* on *arrival rate* and *service rate* entities to arrive closer to their target solution. During this interaction, the computational coupling allows facilitate student understanding of the data dependencies through visualised computational calculations in graphical and equational formats.

- ***Concept Descriptor 9:*** *Multiple output solutions.*

  TUI Design Guideline: *Deployment of dynamic information for comparative assessment.*

  This complexity descriptor is facilitated through TUI frameworks by providing the ability to engage students in more active cognitive and constructivist learning processes, along with their conceptual understanding. In line with the latter pedagogy, TUI systems enable students to creatively express and explore the different potential and plausible solutions through the dynamic construction of entity permutations and relational exploration. Simultaneously, the ability to externalise representations through interwoven physical and digital domains, enables TUI designs to aid in computationally offloading alternative output solutions through tangible and visual interactions. This process facilitates the cognitive interrogation of multiple potential solutions through objective reflection and individual '*backtalk*' learning activities.

  The interactive design considerations undertaken within the *Multi-threaded Task Scheduling* (section 5.5) framework, enabled students to explore potential design solutions through tangible and psychomotor engagement with physical models, whilst assigning *process tasks* on *computational threads*. At each instance, the relational dependencies were explained to students in the derivation of a potential output solution by dynamically animating the *processing load schedules* of *each concurrent thread*. From a cognitive perspective, the exemplified TUI framework enabled students to reflect on the efficacy of the derived outcome, with respect to other explored alternatives through the design of comparative dashboards. In addition, through computational interfacing with hardware resources, the TUI system provided the ability to simulate and calculate process load and execution times, which provided students additional metrics to compare and evaluate the multiple output solutions designed.

- ***Concept Descriptor 10:*** *Integrated functional processes.*

  TUI Design Guideline: *Exposure of interactive entity attributes.*

  The abstract representation of combined operations and processes is elevated through educational TUI architectures by their innately larger interface paradigm. In embracing embodied cognition theories, TUI designs enable students to manifest abstracted attributes and procedures onto physical entities. This tangible representation aids the engagement of learner's *perceptual intelligence* and symbolic learning. The visual-spatial feedback provided through tabletop TUI architectures, further present the opportunity for educators to facilitate the design and representation of abstracted information and internal entity processes. These design factors further help reduce the cognitive load required by students to mentally envision and understand integrated conceptual models and processes.

  In the *Computer Network Protocols* TUI framework, the integrated functional processes between *router* entities were explicated through the design of visual and haptic interactions. The perceptual coupling of *parameter information* and *internal data tables* with physical entities, allows students to mentally apprehend the integrated conceptual model. Furthermore, the interactive embodiment of familiar tangible models provides students with a range of manipulation affordances which enable the configuration of internal functional attributes and processes. These inner operations are explicated by the *Computer Network Protocols* framework, whereby dynamic visual animations guide students towards understanding functional and computational processes influencing the integrated outcome of a *designated router election* protocol. The entity and operational dependencies for deriving a conceptual outcome are further aided by the design of visuospatial animation in TUI frameworks. Through this methodology, students are able to visualise the internal *packet data,* and information flow, within a *computer network* through interactive engagement of conceptual entities.

- ***Concept Descriptor 11:*** *Theoretically focused.*

  TUI Design Guideline: *Contextualisation of tangible interaction within conversant scenarios.*

  The tangible interactive aspect of TUI architectures instils the design opportunity to contextualise and represent abstracted concepts in physical and digital form. This mode of conceptual delivery intrinsically aids constructive learning integration through the application of theoretical notions on real-life environments. This allows educators to employ various instances of exemplification when actively enabling the effective teaching and learning of abstracted concepts and operations. From a cognitive perspective, this capacity provides students with the ability to build flexible and relatable mental models through the inherent concretisation of conceptual attributes. The dynamic design of tangible and digital representations also provides TUI frameworks the ability to provide different symbolic representations towards concepts - through the mutation of embodied cognition with physical interactions.

  The design considerations undertaken in *Queuing Theory Computation* framework, ensure that the TUI framework provides a dynamic and illustrative exemplification of the abstract mathematical models entailed within the concept. To this end, computational calculations and results are embodied within a contextual visualisation. This provides students with the ability to engage with the underpinning concepts of the simulation, by externalizing their theoretical model within a familiar scenario such as *router buffers* and *processing units* in a *computer network* domain. Through the visual simulation of *incoming datagrams* and *core processor speeds*, students are able to interactively engage with abstracted probability distributions, hence promoting their conceptual understanding through experimental and reflective learning activities. Furthermore, the capacity of dynamically introducing different sets of physical tangible models provides the *Queuing Theory Computation* TUI framework, with the unique ability to represent the conceptual model within variant contextual scenarios. As exemplified within this TUI setup, via the use of different tangible objects relating towards a *corporate business environment*, students can interactively engage with abstracted concepts at different symbolic levels of familiarity. This accentuates the ability of educational TUI frameworks to aid students in applying and adapting their conceptual understanding, through flexible and varying instances of problem-based learning.

- ***Concept Descriptor 12:*** *Unrelatable internal entities.*

  TUI Design Guideline: *Guided engagement through associative constraints on interactive degrees-of-freedom.*

  Leveraging on interactive interface design, TUI frameworks provide the capability to aid the educational engagement of students with abstracted notions and entities which lack real-life referents. This is partially achieved through the digital coupling between tangible and virtual information, providing students with the capacity to express entities and attributes beyond what is practically feasible. Through this unconstrained interactive association, tangible design affords the opportunity for the exploration of combinatorial architectures which cannot be reflected in a practical simulation. Moreover, through engagement with embodied haptic interaction and graphical visual schemas, students can transfer abstracted functions and entity attributes onto physical constructors, thus taking advantage of different VARK learning modalities which support the development of a heightened sense of interactive intuitiveness.

As exemplified in the *Multi-threaded Task Scheduling* framework, TUI design was adopted to represent the intangible and unrelatable concepts of *thread process scheduling* and *CPU execution*. Through haptic and psychomotor interaction, instruction tasks are allocated to different process threads, creating combinatorial possibilities which are otherwise unfeasible for experimental investigation. The tangible objects within this TUI framework were further designed to assert identifiable representations and '*conceptual inference*' to the abstracted entities by embodying commonly used *computational processes* and *task dependencies*. In tandem with perceptually coupled visual interaction, the TUI framework provided instinctive guidance for entity interaction through the designed dynamic reduction, in degrees of interactive freedom - thus aiding students to learn and understand better the functional properties of *internal CPU thread processing* and *task allocation dependencies*.

- ***Concept Descriptor 13:*** *Contextually dependent processes.*
  TUI Design Guideline: *Utilization of an interactive design schema.*

The versatile nature of TUI interfaces also provides the educational technology with the ability to design interactions that alter dynamically in contextual adoption. Underpinned by the capabilities of deploying interactive design schemas, TUI frameworks provide the ability to help students actively understand abstract concepts which require mental processes or interactions that are relevant to situational aspects. From an embodied pedagogy perspective, TUI systems facilitate the interaction within environmentally contextual case scenarios, by tangibly embedding situational entities through representative physical objects and models. Furthermore, the design of informational relations that mirror familiar environments for students, reduces the cognitive load required for contextual mapping, thus allowing learners to focus their cognitive resources on conceptual learning.

The design of the TUI framework developed for *Database Normalisation Processes* capitalizes on context familiarity by integrating an *educational student data* example. Through representational models, the framework embodied commonly associated entities with educational settings such as *student ID number* and *exam grade*. Furthermore, the digital visualisation of typical data for each tangible entity, provides students with the ability to mirror their conceptual understanding with realistic information content and patterns. This facilitates the students' pedagogical pursuit by simplifying their cognitive mapping of abstracted notions and intrinsically aids their learning activities.

7.3.3 Application to TUI design elements

In line with the TUI design sections adopted within chapter 5, the detailed guidelines were categorised on design process elements of *tangible design, tangible interaction* and *learning activities.* These interrelated elements, defined in Table 7.3, segregate the different stages of TUI framework design.

Table 7.3: Definition of entity design taxonomy

Design Element	Definition
Tangible design	The external representation of entities through physical modalities of visual, tactile, and auditory attributes. This design element entails the consideration of material, texture, colour, shape, and active sensors used on tangibles.
Tangible interaction	The interlaced design of physical and digital interaction paradigms through perceptual and computational coupling. This TUI design element defines the schema of interaction through tangible manipulation and visual feedback.
Learning activities	The pedagogical design of the TUI technology within educational contexts, is built to enhance student learning. This design element encompasses a multitude of learning styles, modalities, and theories to aid the conceptual understanding of abstract and complex notions.

Whereas each respective element is to some extent conceived, designed and implemented individually prior to integration within a TUI system, the successful design of a TUI framework necessitates the holistic and united consideration of all design elements collectively. Thus, as visualised in Figure 7.2, these design elements encompass the main design opportunities over which the proposed guidelines can be deployed.

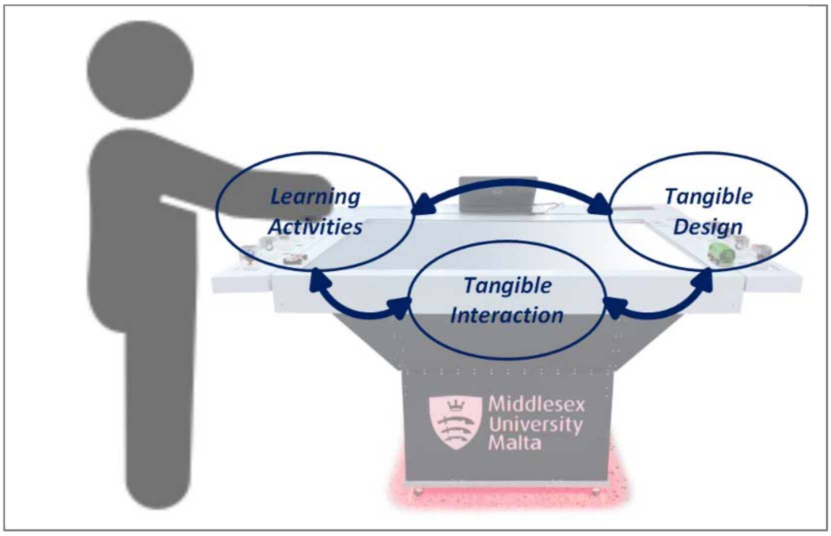


Figure 7.2 TUI design elements.

To this end,

Table 7.4 outlines the applicability mapping of the guideline set defined in section 7.3.2, to facilitate the conceptualisation of TUI learning environments. Furthermore, whilst aiding the focus of design guidelines application on individual element stages, this taxonomy further provides an understanding of the relational importance provided by other elements on design decisions. These correlative relations provide an understanding of the dependent considerations required in TUI design for the integration of abstract and complex concepts within HEI. To this end, whilst each design consideration intrinsically effects the holistic design aspects of TUI frameworks, the ordinal scale adopted in

Table 7.4 exposes the impact of each guideline in relation to the constituting TUI design elements for the effective application of a TUI frameworks towards HE concepts.

Table 7.4: Design guidelines applicability on TUI design elements

Design Guidelines		Tangible Design	Tangible Interaction	Learning Activities
1	Development of interactive tiered interfaces	Low	Medium	High
2	Embodiment of icon representations and associative patterns	High	High	Low
3	Integration of information through tight physical and digital coupling	Medium	High	Medium
4	Utilisation of active tangibles for computational representation	High	High	Low
5	Provision for constructive interactive topologies	Low	High	High
6	Design of interactive segmentation	Low	Medium	High
7	Reactive design for real-time data sensing through active manipulatives	Medium	High	Low
8	Support for concurrent interaction through distributed entities	Medium	High	Medium
9	Deployment of dynamic information for comparative assessment	Low	High	Medium
10	Exposure of interactive entity attributes	Medium	High	Low
11	Contextualisation of tangible interaction within conversant scenarios	High	Medium	Medium
12	Guided engagement through the dynamic constraint of interactive degrees-of-freedom	High	High	Low
13	Utilization of an interactive design schema	Low	High	High

Chapter 8 Conclusion

In line with the research question defined in chapter 1, this dissertation has sought to analyse the suitability and effectiveness of designing TUI frameworks for teaching and learning abstract concepts. In contrast to mixed literature on the effectiveness of tangible interfaces to aid education (Marshall, Price and Rogers, 2003; Shaer and Hornecker, 2009; Sullivan, Bers and Pugnali, 2017), the evaluation carried out within this research categorically outlines and assesses the capacity of tangible technology to aid in student learning. More specifically, through empirical evaluation, the study analyses the suitability for the purposely designed TUI educational frameworks to overcome the practical and pedagogical burdens experienced in explaining complex threshold concepts in HEIs (Catala *et al.*, 2011; Goh *et al.*, 2012; Shaer *et al.*, 2014; Skulmowski *et al.*, 2016).

Addressing the physical limitations and constraints in effectively deploying TUI architectures to scaled learning environments, outlined by Cuendet and Dillenbourg (2013) and Devi and Deb (2017), this research proposed and developed a TUI tabletop architecture for HEI usage. The latter design presented a calibrated interactive surface of 1.3m^2 which enhanced the ability to extend abstract and concept designs through spatial and smart-peripheral configurations. Furthermore, the physical dimensions and construction form-factor of the proposed design allowed the TUI architecture to handle a larger cohort of adult students engaged in collaborative learning, whilst providing ease of portability and technical setup.

Through the development of various TUI frameworks on this architecture, the research investigated the effectiveness of designing a tangible interaction learning style to aid in the threshold concept understanding of higher educational subjects within computational science and technology. In line with research consensus for evaluating educational technology (Kazu, 2009; Winne and Nesbit, 2010; Wu, 2014), the study undertook a holistic assessment of academic achievement and satisfaction brought forward by the introduced design of this technology.

To this end, the ability of the designed TUI frameworks to engage students within effective active learning styles was directly assessed with respect to traditional lecturing methodologies for threshold concepts such as; *Queuing Theory, Database Normalisation, Multi-Threaded Task Scheduling*, and *ROS*. As summarised in Figure 8.1, the academic performance gain registered by students in these instances has been validated through a comparative assessment methodology, defined in section 5.1, which outlined the students' acquired knowledge improvement through different teaching and learning modalities.

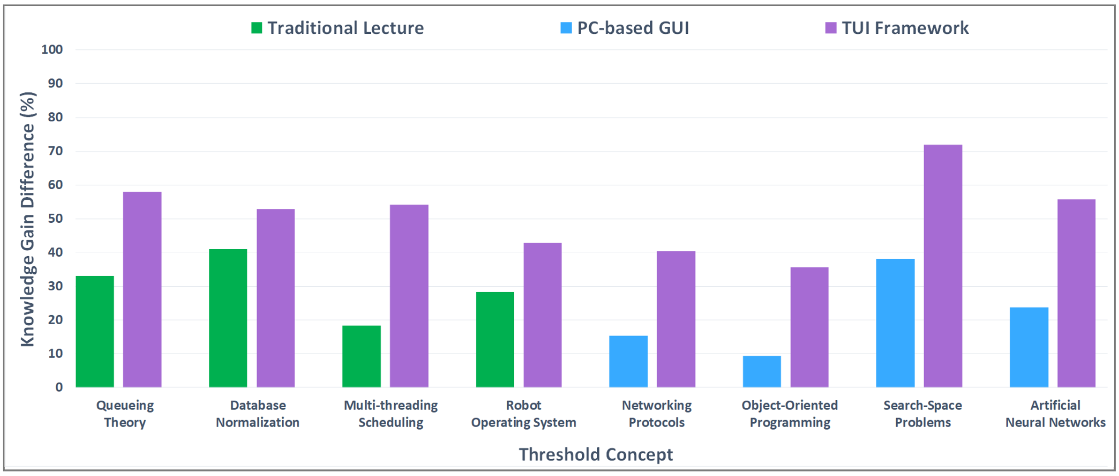


Figure 8.1 Comparative analysis of student knowledge gain from an experimental evaluation of different educational technologies used to teach and learning threshold concepts in computational science and technology.

Providing direct evidence in response to the reservations cast in research on the effectiveness of tangible technology with respect to conventional graphical user interfaces for learning tasks (Marshall, 2007; Zaman *et al.*, 2012; Zuckerman and Gal-Oz, 2013), the study further compares TUI deployment with respect to conventional PC-based technology. Through experimental analysis on threshold concepts such as *Networking Protocols* and *Object-Oriented Programming*, the effectiveness of the proposed TUI frameworks was prominently assessed against the current software adaptions customary within laboratory practices to teach computational science and technology topics.

As shown from the aggregate results in Figure 8.1, the deployment of TUI frameworks for abstracted concepts provided an enriched interactive environment for ingraining active learning methodologies beyond what is commonly provided through PC-based educational developments. Furthermore, within deployment instances for state-search-space and artificial neural network concepts, the effectiveness imparted through tangible interaction was unequivocally validated through explicit comparison with identical GUI based software developments that were optimised for PC-based interaction. Thus, through the novel adaption of tangible design elements including; interactive tabletop peripherals, graphical design factors and active embedded manipulatives, the study explores the capacity of TUI frameworks to overcome technological limitations currently experienced in teaching and learning within HEIs.

In compliment to evaluating the academic achievement enhancement brought about by the design and development of TUI frameworks, the study further investigates the students' satisfaction aspect of educational technology through acceptance modelling for behavioural intention to use (Teo, 2009, 2016; Wu, 2014; Al-Samarraie *et al.*, 2017; Joo, So and Kim, 2018). Through the development, an adapted evaluation framework for educational technology acceptance modelling (TAM4Edu), a set of determinants are considered to assess the suitability of the designed TUI frameworks for adoption in HEI contexts. Modelled on the core acceptance constructs of perceived ease of use and perceived usefulness, the empirical score difference obtained for these determinants from a population sample of 105 students are shown Figure 8.2.

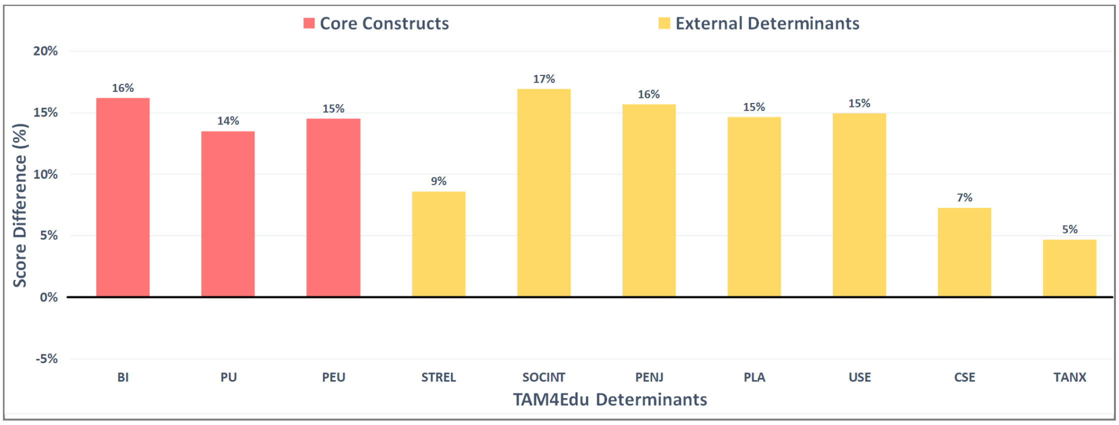


Figure 8.2 Differential analysis of TAM4Edu determinant scores from an experimental evaluation of TUI framework adoption with respect to conventional HEI educational technologies used to teach and learn threshold concepts.

In support of the research question addressed by this study, the results in Figure 8.2 reflect a homogeneous enhanced perception of TAM4Edu acceptance constructs evaluated from the adoption of TUI technology with respect to conventional educational technology setups. Thus, the experimentally validated difference in student perceptions attests to the suitability of the designed TUI frameworks to effectively aid teaching and learning within HEI education.

Subsequently, a categorical analysis is undertaken in light of the experimental results to reflect on the theoretical and practical pedagogical considerations adopted within the proposed TUI frameworks. The efficacy and suitability of tangible technology is thus empirically discussed in relation to the capabilities and capacity of TUI frameworks to support and engage students through various educational pedagogies. Founded upon these design reflections and structured on a set of abstract and complex concept descriptors for computational science and technology education, the study ultimately defines a set of TUI design guidelines for the effective development of tangible frameworks within HEI contexts.

8.1 Reflective SWOT Analysis

Underpinned by the experiences, challenges and results obtained within this study, this section provides a reflective critique on deploying TUI systems as an educational technology. Through an in-depth SWOT analysis outlined in Figure 8.3, a comprehensive perspective is adopted towards assessing the potential of the proposed tangible design framework towards generalised teaching and learning in higher education.

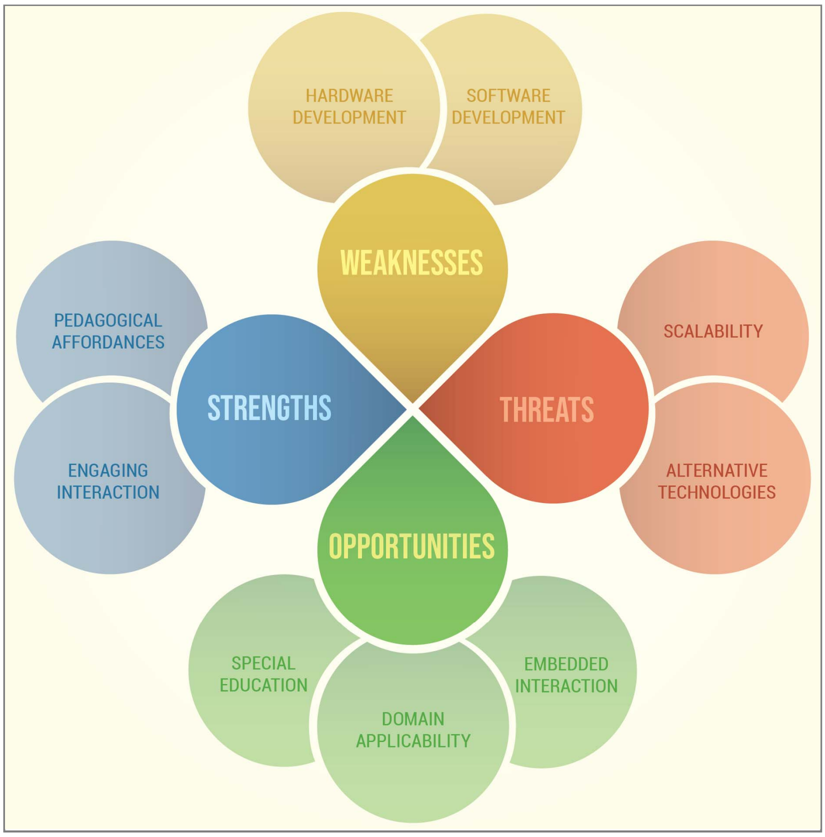


Figure 8.3 SWOT evaluation of TUI frameworks adopted in educational technology.

These analytical elements are further elucidated in a structured approach within this section, outlining the capacity of the proposed research to validate the strengths defined whilst addressing the inherent weakness in TUI frameworks. Furthermore, an analysis of opportunities and threats are further detailed in section 8.2, providing investigative directions of research to overcome current adoption burdens.

8.1.1 Strengths

- ***Pedagogical Affordances:***

As empirically and theoretically reviewed in section 7.1, this research corroborates the capacity of TUI frameworks to effectively engage students in active learning pedagogies. The summative and formative results obtained on the proposed the TUI framework designs outline the capabilities of tangible technology to innately integrate cognitive learning modalities and pedagogical approaches in teaching and learning HEI threshold concepts. As defined within the TUI design guidelines proposed in section 7.3, the inherent ability to interweave the digital realm onto physical manipulatives affords TUI systems the ability to exemplify highly complex and abstract notions through constructivist and collaborative approaches. Furthermore, the dynamic nature of representing information through embodied interaction provides tangible technology with the ability to exploit a variety of Visual, Aural, Read/Write and Kinesthetic (VARK) modalities to yield an equally effective educational experience amongst students with different learning preferences. Whilst these pedagogical affordances have been empirically validated on younger audiences, this study expands their applicability towards describing more abstract and complex concepts present in HEI learning.

- ***Engaging Interaction:***

The empirical analysis on the suitability of TUI frameworks in HEI contexts was validated through the adoption of the proposed TAM4Edu framework within chapter 6. The comparative assessment of educational technologies undertaken with this model in section 6.3.3 highlights the augmented capacity of TUI frameworks to actively engage higher education students within their pursuit to internalise threshold conceptual knowledge.

Moreover, the external construct analysis provides a concrete indication of the capabilities of TUI frameworks to enhance the *perceived enjoyment* and *perceived lecture attention* by students whilst interacting with the system. These results are further supported by statistically significant differences registered by students in aspects of *social interaction* and *usability* with respect to conventional educational technology thus confirming the strength of tangible frameworks to effectively engage more mature audiences in HEIs.

8.1.2 Weakness

- ***Hardware Development:***

Albeit TUI architectures differ within their form-factor deployment, the embodiment of digital computation within tangible representation demands the need for dedicated hardware requirements. Whilst these are often inexpensive to procure, the bespoke nature of tangible technology often demands the need for dedicated design and development of a TUI architecture. Thus, the integration of TUI frameworks within educational context relies heavily on technical expertise in computer engineering to design and configure a technological solution interlacing electronic components and tangible hardware. Moreover, the customised aspects explored within the TUI literature further demand the inclusion of technical specialists to calibrate and operate the tangible frameworks, thus hindering the attractiveness and capacity for TUI deployment in technically constrained circumstances.

Whilst this weakness is prominent within all the developments of TUI systems, the proposed research aims to partially address this limitation through the design of a tabletop TUI architecture as detailed in chapter 4. The technical details defined within this research together with the comprehensive considerations addressed through the TUI design aim to provide an architectural blueprint for developing a TUI tabletop architecture as an educational technology. Furthermore, the designed TUI architecture mitigates the challenges faced from a portability and configuration perspective by proposing specific design considerations to facilitate the adoption of TUI frameworks in HEI contexts within minimal technical requirements.

- ***Software Development:***

The development of TUI frameworks for abstract and complex concepts commonly demands the need for both academic domain expertise as well as advanced levels of computer science knowledge to interlink digital computation and visualisation with tangible attributes. This requirement commonly constrains the development and use of TUI frameworks within restricted areas of education. Typical to software architectures, this implies that customised solutions need to be developed in a specialised approach for each distinct educational context. Moreover, because of the heretofore confined research on tangible framework proposals in comparison to other technological solutions, this weakness is further amplified within an educational context due to limited framework available for integration. Regrettably, this aspect hinders the proliferation of tangible technology further as the pedagogical potential harboured by TUI frameworks is commonly overshadowed by the significant burdens on educators to design and develop bespoke experimental setups with often fickle and uncertain effectiveness results.

By means of the proposals described in chapter 5, this research aims to partially mitigate this predicament by presenting eight empirically evaluated TUI frameworks for deployment within computational science and technology-based concepts. The software and tangible interactions detailed within these frameworks further provide a comprehensive understanding of software design and development techniques used to computational embed effective digital representations within tangible frameworks. These aspects are additionally defined within the TUI design guidelines proposed in section 7.3, which aim to lessen the knowledge barrier encountered in designing and integrating TUI elements in HEI.

8.1.3 Opportunities

- ***Domain Applicability:***

The versatility provided by tangible interaction design elements in mitigating abstract and threshold concepts within HEI outlines the potential for the proposed research to be expanded further amidst different educational domains. As critically detailed with the literature taxonomy in section 2.2, the research and development of TUI in higher education is still within its outset providing an opportunity for investigation and deployment of tangible technology in a myriad of applications and contexts.

Whilst the TUI frameworks explained in chapter 5 cover a diverse set of highly complex and abstract notions commonly encountered within computational science and technology subjects, the reflective analysis undertaken in section 7.2 presents a systematic review on the constructs of these notions, implicitly outlining the capacity of TUI design to effectively expound alternate contextual deployments throughout the various threshold concepts experienced in HEI studies.

- ***Special Education:***

The enriched cognitive and physical learning environment created through interlacing digital information with tangible interaction provides an inherent capacity for TUI frameworks to address teaching and learning challenges faced when educating students with special conditions. This opportunity has been investigated within niche research communities as detailed in section 2.2.3, however, most of these contributions once more consider children as their prime audience and mostly deal with disabilities and difficulties encountered within Autistic Spectrum Conditions (ASC). The application of TUI frameworks within higher education thus still poses interesting research opportunities in understanding further the implications and potential of tangible interaction design to aid bridge these educational difficulties. Further to the potential to aid ASC students in understanding highly complex and abstract concepts, the dynamic interweaved coupling between digital information and physical representation holds additional opportunities for potentially mitigate challenges faced by other commonplace disorders within HEIs which thus far have not received explicit investigation.

- ***Embedded Interaction:***

Some of the TUI frameworks proposed within chapter 5 approach a novel tangible interactive environment whereby active physical manipulatives are deployed embedding autonomous computational architectural units which undertake distributed wireless communication with the TUI central processing server. Within the TUI frameworks investigated in this research, this innovative extension to tabletop TUI architectures provided an additional interactive paradigm which mitigated representational and interactive challenges faced when explaining abstract and complex concepts.

Whilst this interactive paradigm has been explored through different tangible configurations using a range of input sensing devices and output actuators, the latter constitute a small subset of the electronic components arsenal that can be adopted within active tangibles and peripherals. Thus, this research has yielded an extended opportunity for TUI frameworks which enhance their interactive and educational capacity through an interlinked tabletop and embedded TUI architecture.

8.1.4 Threats

- ***Alternative Technologies:***

Modern technologies, led by the innovation of smart and emerging devices, has presented educators with revolutionary platforms to transform the way teaching and learning is performed. As analysed by the latest hype cycles for educational technologies, alternative technologies such as Augmented Reality (AR), Virtual Reality (VR) have furthered the deployment of personal devices in ubiquitous educational approaches (Laru and Järvelä, 2013; Banica, 2014). These alternatives within the Reality-Based Interaction (RBI) spectrum pose a substantial substitute threat to TUI frameworks due to their more advanced pace in research progression and proliferation. This was empirically outlined within the study by Gartner (2017), whereby these alternate technologies significantly outpace smart workspaces such as TUI architectures and are thus closer to the '*Plateau of Productivity*' stage within the latest issued educational and emerging technologies hype cycle (Calhoun Williams, 2017).

- ***Scalability:***

As detailed within the literature taxonomy in chapter 2, TUI frameworks inherently embody an augmented capacity to engage students in collaborative pedagogies. This pedagogical attribute was theoretically reviewed in section 7.1.4 and empirically validated through both summative and formative measures within this study. Alas, albeit specifically designed to simultaneously handle a larger cohort of adult students in comparison to current developments within tangible educational technology literature, the TUI architecture proposed in chapter 4 still presents a finite limit on its capacity to effectively educate larger volumes of concurrent students.

This deployment threat is common to the majority of TUI architectures reviewed in section 4.1, whereby a linear scalability model needs to be employed as student's cohorts increase in size. Moreover, the specialisation of different architectural frameworks to unique concepts further extends the impact of this attribute whereby educational institutions which would require to design and/or procure several TUI systems to effectively deliver their educational content.

8.2 Research Limitations

Albeit numerous efforts have been adopted to reduce the potential weaknesses and shortcomings in undertaking the research methodologies, inherent deficiencies were still encountered which pose interesting domains of research for expanding the validation of the investigated research hypothesis. To this end, this section aims to elaborate on some of the limitations experienced within this study which would further enrich the detailed contributions.

- ***Domain Constraint:***

The execution of this research was undertaken within an HEI environment in which science and technology courses are significantly predominant. Whilst a variety of programmes are offered within this faculty, the research had very limited exposure to alternate academic disciplines. The latter could have contributed further to the research methodology through the analysis and reflection on TUI frameworks from distinct perspectives. Furthermore, the study has been constrained towards the consideration of computing science and technology concepts in HEI. The potential versatility of TUI design elements towards dissimilar concepts is still unexplored, with abstract and complex concepts potentially posing unexplored challenges towards equal TUI effectiveness and suitability.

- ***Demographic Constraint:***

The evaluation methodology conducted within this study was inevitably biased by the limited and specialised demographics of participants enrolled. Albeit that experimental validation on TUI frameworks was conducted over several academic cycles, the small-size availability of volunteering participants on campus was consistently constrained by admission figures within computational science and technology courses. This implied that a characteristic demographic pattern was also observed within participant data, whereby significant skewness was experienced in participant gender and age distributions. Furthermore, the specialised knowledge and skillset held by participants provided a challenging environment for assessing TAM4Edu constructs such as *Technology Anxiety*, whereby unreliable kurtosis values were observed within the collected dataset.

- ***Analytical Constraint:***

Through the investigation of the research question explored within this study, substantial research has been devoted to understanding and applying the correct statistical techniques within the analytical methodology. Whilst expert guidance was sought to validate the appropriateness of the adopted strategies, the limited knowledge and expertise within the domain inherently imply that an even more enriched understanding of this research could be exploited. Further analysis of the evaluated dataset might potentially uncover deeper investigation towards the effectiveness and suitability of TUI frameworks as well as aid in the design and interpretation of advancements on TUI elements.

- ***Technological Availability Constraint:***

Although the research methodology has adopted and analysed a variety of educational technologies as experimental controls when evaluating the effectiveness and suitability of TUI frameworks in HEI, an inherent limitation experienced by the study was the constrained variety if available technology in adoption. Whilst the investigation has considered the conventional and common educational technologies proliferated amongst most HEI environments, the research had limited access to emerging educational technologies. Whilst the use of Augmented Reality (AR) and Virtual Reality (VR) environments is still a niche within educational research, the direct comparison with these innovative interactive technologies could yield to significantly enriched reflection on TUI frameworks.

- ***Time Constraint:***

The agile methodology adopted throughout this research has constrained the adoption of short-term design and evaluation of experimental cycles. The undertaking of a longitudinal scoped study could hence further the limitations experienced within this research by analysing the effectiveness and suitability of TUI design elements throughout consecutive academic years. The effect on pedagogical affordances investigated within this research could potentially yield interesting observations which have been unexplored during this study. Furthermore, additional evaluations along extended timelines could aid in providing more conclusive evidence on the students' behavioural attitude and acceptance towards the proposed TUI technology.

8.3 Identification of Further Research

Further to the opportunities detailed within the SWOT analysis, through the experience of this study, several aspects of tangible technology were identified which require additional investigation to overcome the weakness and threats currently manifested within TUI frameworks. Albeit the study proposes a set of novel TUI frameworks for teaching and learning abstract concepts in computational science and technology-based subjects, the research domain on educational TUI approaches is still largely unexplored in the literature with most research focusing on bespoke developments and contexts. To this end, this section defines tangential areas of research on TUI systems which merit further study to expand the applicability of tangible technology within educational contexts.

- ***Scalable TUI development:***

Whilst research interest in tangible technology has garnered popularity over the past years, the limited disruptive contributions in the domain have led most TUI systems to rely heavily on the need for computer science knowledge in the design and development of functional architectures. In contrast to the development of PC-based software environments which avail from innumerable libraries and APIs to aid in rapid application prototyping, the integration of tangible technologies still demands advanced levels of technical and programming knowledge for successful integration. Whilst the use of game development platforms such as Unity™ facilitate the design of graphical elements, the development of a complete tangible interface still entails significant computer science challenges to integrate frameworks based on computer vision platforms and code-intensive logic programming. Unfortunately, these barriers often hinder the availability and design capacity of TUI technology outside of research centres by presenting a skillset impasse for the development and adaptation of TUI frameworks by non-technical educational professionals. Consequently, this constraint presents an interesting research problem for the mitigation of programming and software development challenges during the design and integration of educational TUI frameworks.

- ***Scalable TUI architecture:***

Following an analysis of different TUI architectures and deployments in section 4.1, a common limitation exhibited within these form-factors is their capacity to scale up towards sizable audiences and thus allowing for collaborative interaction from multiple students concurrently. Albeit the proposed tabletop architectural design in chapter 4 is able to cope and engage with an increased amount of higher education students compared to developments proposed in the literature, a finite capacity is still inherently present with the architecture. Furthermore, whilst providing an appropriate and facilitated design guide towards physically developing a TUI construction, the materialisation of a TUI architecture still poses financial and manufacturing burdens on educators.

These hindrances are further aggravated when extending TUI technology towards larger student lecture groups, whereby the latter often demands that multiple TUI sets are procured and maintained by educational institutions. Alas, these factors have consequently dampened the interest in adopting and integrating TUI frameworks within education. To this end, an interesting area for further research lies in attempting to mitigate this challenge through the design and development of novel TUI architectures which can address larger student cohorts whilst reducing the scalability and hardware strains currently present in TUI architectures.

- ***Technology Integration:***

Although perceived as a substitute threat towards deployment of TUI frameworks in Figure 8.3, the proliferation and research progress of alternate technologies provide an interesting research opportunity for design integration. Through the use of widespread hardware such as mobile and tablet platforms, developments in AR and VR can be further explored for their suitability and effectiveness in integration with TUI frameworks. This niche research area on

Tangible Augmented Reality (TAR), has garnered interest over the past years in design and commercial domains for its ability to introduce a complimentary set of interaction paradigms to users facilitating their undertaken task (Billinghurst, Kato and Poupyrev, 2008; Vinot *et al.*, 2014; Fan, Antle and Sarker, 2018).

In light of the recent advancements towards this amalgamated technological solution, an unexplored research area has been identified in relation to the design and adoption of TAR technology as an effective and suitable educational technology within HEIs. Thus, the inherent benefits of amalgamation with AR or VR platforms provide an augmented approach to TUI frameworks which can be potentially investigated for their capacity to represent and interact with further abstract and complex concepts in educational contexts.

References

Abdul Razak, A. and Connolly, T. M. (2013) 'Using games as a context for interdisciplinary learning: A case study at a Scottish primary school', in *IEEE Global Engineering Education Conference, EDUCON*, pp. 1084–1092. doi: 10.1109/EduCon.2013.6530243.

Abdullah, F. and Ward, R. (2016) 'Developing a General Extended Technology Acceptance Model for E-Learning (GETAMEL) by analysing commonly used external factors', *Computers in Human Behavior*. Elsevier Ltd, 56, pp. 238–256. doi: 10.1016/j.chb.2015.11.036.

Adams, A. and Cox, A. L. (2008) 'Questionnaires, in-depth interviews and focus groups', in *Questionnaires, in-depth interviews and focus groups*. Cambridge, UK: Cambridge University Press, pp. 17–34.

Adams, D. A., Nelson, R. R. and Todd, P. A. (1992) 'Perceived Usefulness, Ease of Use, and Usage of Information Technology: A Replication', *MIS Quarterly*, 16(2), p. 227. doi: 10.2307/249577.

Africano, D. *et al.* (2004) 'Designing tangible interfaces for children's collaboration', in *Extended abstracts of the 2004 conference on Human factors and computing systems - CHI '04*, p. 853. doi: 10.1145/985921.985945.

Agarwal, R., Sambamurthy, V. and Stair, R. M. (2000) 'Research Report: The Evolving Relationship Between General and Specific Computer Self-Efficacy—An Empirical Assessment', *Information Systems Research*, 11(4), pp. 418–430. doi: 10.1287/isre.11.4.418.11876.

Agostinho, S. (2005) 'Naturalistic Inquiry in E-Learning Research', *International Journal of Qualitative Methods*. doi: 10.1177/160940690500400102.

Agrawal, A., Gans, J. S. and Goldfarb, A. (2017) 'What to Expect From Artificial Intelligence', *MIT Sloan Management Review*, 58(3), pp. 22–26.

Agrawal, H. and Sorathia, K. (2013) 'AstroGrasp: a tangible user interface for teaching basic astronomy concepts', *Proceedings of the 11th Asia Pacific Conference …*, pp. 123–128. doi: 10.1145/2525194.2525207.

Ahmad, A. S. *et al.* (2014) 'A review on applications of ANN and SVM for building electrical energy consumption forecasting', *Renewable and Sustainable Energy Reviews*. Pergamon, 33, pp. 102–109. doi: 10.1016/j.rser.2014.01.069.

Ahmad, B. I. and Ahlan, A. R. (2015) 'Reliability and validity of a questionnaire to evaluate diabetic patients' intention to adopt health information technology: A pilot study', *Journal of Theoretical and Applied Information Technology*, 72(2), pp. 253–264.

Ajzen, I. (1985) 'From Intentions to Actions: A Theory of Planned Behavior', in *Action Control*, pp. 11–39. doi: 10.1007/978-3-642-69746-3_2.

Ajzen, I. (1991) 'The theory of planned behavior', *Organizational Behavior and Human Decision Processes*, 50(2), pp. 179–211. doi: 10.1016/0749-5978(91)90020-T.

Al-Adwan, Amer, Al-Adwan, Ahmad and Smedley, J. (2013) 'Exploring students acceptance of e-learning using Technology Acceptance Model in Jordanian universities', *International Journal of Education and Development using Information and Communication Technology*, 9(2), pp. 4–18.

Al-Alak, B. A. and Alnawas, I. A. M. (2011) 'Measuring the acceptance and adoption of e-learning by academic staff', *Knowledge Management and E-Learning*, 3(2), pp. 201–221.

Al-Aulamie, A. *et al.* (2012) 'The effect of interinsic motivation on learners' behavioural intention to use e-learning systems', in *2012 International Conference on Information Technology Based Higher Education and Training, ITHET 2012*. doi: 10.1109/ITHET.2012.6246057.

Al-Gahtani, S. S. (2016) 'Empirical investigation of e-learning acceptance and assimilation: A structural equation model', *Applied Computing and Informatics*, 12(1), pp. 27–50. doi: 10.1016/j.aci.2014.09.001.

Al-Rahmi, W. M. *et al.* (2018) 'A model of factors affecting learning performance through the use of social media in Malaysian higher education', *Computers and*

Education. Pergamon, 121, pp. 59–72. doi: 10.1016/j.compedu.2018.02.010.

Al-Samarraie, H. *et al.* (2017) 'E-learning continuance satisfaction in higher education: a unified perspective from instructors and students', *Studies in Higher Education*. Routledge, pp. 1–17. doi: 10.1080/03075079.2017.1298088.

Alaman, X., Mateu, J. and Lasala, M. J. (2016) 'Designing virtual world educational applications', *2016 IEEE Global Engineering Education Conference (EDUCON)*. IEEE, (April), pp. 1134–1137. doi: 10.1109/EDUCON.2016.7474697.

Alenezi, A. R., Karim, A. M. A. and Veloo, A. (2010) 'An empirical investigation into the role of enjoyment, computer anxiety, computer self-efficacy and internet experience in influencing the students' intention to use e learning: A case study from saudi arabian governmental universities', *Turkish Online Journal of Educational Technology*, 9(4), pp. 22–34. doi: 10.1111/j.1548-1425.2012.01362.x.

Ali, M. *et al.* (2018) 'Assessing the e-learning system in higher education institutes: evidence from structural equation modelling', *Interactive Technology and Smart Education*, 12 March, pp. 00–00. doi: 10.1108/ITSE-02-2017-0012.

Almgren, J. *et al.* (2005) 'Tangible User Interface for Chemistry Education: Visualization, Portability, and Database', *Visualization, Portability, and Database. Proc. SIGRAD 2005*. Univ, (016), pp. 19–24.

Alsafran, E. and Brown, D. S. (2012) 'The relationship between classroom computer technology and students' academic achievement', *Research in Higher Education Journal*, 15, pp. 1–19.

Alves, A. *et al.* (2010) 'Reactoon: Storytelling in a tangible environment', in *DIGITEL 2010 - The 3rd IEEE International Conference on Digital Game and Intelligent Toy Enhanced Learning*, pp. 161–165. doi: 10.1109/DIGITEL.2010.28.

Amershi, S. *et al.* (2005) 'Designing CIspace: pedagogy and usability in a learning environment for AI', *SIGCSE Bulletin*, 37(3), pp. 178–182. doi: 10.1145/1067445.1067495.

Anagnostou, G., Dewey, D. and Patera, A. T. (1989) 'Geometry-defining processors for engineering design and analysis', *The Visual Computer*, 5(5), pp. 304–315. doi:

10.1007/BF01914788.

Anderson, D. *et al.* (2000) 'Tangible interaction + graphical interpretation: a new approach to 3D modeling', *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, 11, pp. 393–402. doi: http://doi.acm.org/10.1145/344779.344960.

Andrews, G. and Halford, G. S. (2002) 'A cognitive complexity metric applied to cognitive development', in *Cognitive Psychology*, pp. 153–219. doi: 10.1016/S0010-0285(02)00002-6.

Andruseac, G. G. and Iacob, R. (2013) 'Exploring the potential of using educational robotics as an effective tool to support collaborative learning', in *E-Health and Bioengineering Conference (EHB)*, pp. 1–4. doi: 10.1109/EHB.2013.6707359.

Ang, K. (2010) 'Teaching and Learning Mathematical Modelling with Technology', *15th Asian Technology Conference in Mathematics*, (December), pp. 17–21.

Antle, A. (2007) 'The CTI framework: informing the design of tangible systems for children', *Proceedings of the 1st international conference on Tangible and embedded interaction*, pp. 15–17. doi: 10.1145/1226969.1227010.

Antle, A. N. *et al.* (2013) 'Youtopia: a collaborative, tangible, multi-touch, sustainability learning activity', *Proceedings of the 12th International Conference on Interaction Design and Children*, pp. 565–568. doi: 10.1145/2485760.2485866.

Antle, A. N., Corness, G. and Droumeva, M. (2009) 'Human-computer-intuition? Exploring the cognitive basis for intuition in embodied interaction', *International Journal of Arts and Technology*, 2(3), p. 235. doi: 10.1504/IJART.2009.028927.

Antle, A. N., Droumeva, M. and Corness, G. (2008) 'Playing with the sound maker: do embodied metaphors help children learn?', in *Proceedings of the 7th international conference on Interaction design and children - IDC '08*, pp. 178–185. doi: 10.1145/1463689.1463754.

Antle, A. N., Droumeva, M. and Ha, D. (2009) 'Hands on what? Comparing Children's Mouse-based and Tangible-based Interaction', *Proceedings of the 8th International Conference on Interaction Design and Children - IDC '09*, p. 80. doi:

10.1145/1551788.1551803.

Antle, A. N. and Wise, A. F. (2013) ‘Getting Down to Details: Using Theory of Cognition and Learning to Inform Tangible User Interface Design’, *Interacting with Computers*, 25(1), pp. 1–20. doi: 10.1093/iwc/iws007.

Arias, E., Eden, H. and Fischer, G. (1997) ‘Enhancing communication, facilitating shared understanding, and creating better artifacts by integrating physical and computational media for design’, *Proc. DIS 1997*, pp. 1–12. doi: http://doi.acm.org/10.1145/263552.263553.

Arif, A. S. *et al.* (2016) ‘Sparse Tangibles: collaborative exploration of gene networks using active tangibles and interactive tabletops’, in *Proceedings of the TEI ’16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI ’16*, pp. 287–295. doi: 10.1145/2839462.2839500.

Ariff, M. S. M. *et al.* (2012) ‘The Effects of Computer Self-Efficacy and Technology Acceptance Model on Behavioral Intention in Internet Banking Systems’, *Procedia - Social and Behavioral Sciences*, 57, pp. 448–452. doi: 10.1016/j.sbspro.2012.09.1210.

Armentano, M. G., Christensen, I. and Schiaffino, S. (2015) ‘Applying the Technology Acceptance Model to Evaluation of Recommender Systems’, *Polibits*, (51), pp. 73–79. doi: 10.17562/PB-51-10.

Armitage, A. F. (2001) ‘Teaching Multitasking to Electronics and Computing Students’, *International Journal of Electrical Engineering Education*. SAGE PublicationsSage UK: London, England, 38(4), pp. 338–347. doi: 10.7227/IJEEE.38.4.7.

Ary, D. *et al.* (2018) *Introduction to research in education*. 10th edn. Wadsworth Publishing.

Asai, K. and Takase, N. (2011) ‘Learning Molecular Structures in a Tangible Augmented Reality Environment’, *International Journal of Virtual and Personal Learning Environments*. IGI Global, 2(1), pp. 1–18. doi: 10.4018/jvple.2011010101.

Astatke, Y. *et al.* (2016) ‘Improving and Expanding Engineering Education in the Middle East and Africa Using Mobile Learning Technology and Innovative Pedagogy’, in *Advances in Engineering Education in the Middle East and North Africa*. Cham: Springer International Publishing, pp. 235–260. doi: 10.1007/978-3-319-15323-0_10.

Atkinson, R. C. and Shiffrin, R. M. (1968) ‘Human Memory: A Proposed System and its Control Processes’, *Psychology of Learning and Motivation - Advances in Research and Theory*, 2(C), pp. 89–195. doi: 10.1016/S0079-7421(08)60422-3.

Atmatzidou, S. and Demetriadis, S. (2015) ‘Advancing students’ computational thinking skills through educational robotics: A study on age and gender relevant differences’, *Robotics and Autonomous Systems*. doi: 10.1016/j.robot.2015.10.008.

Austin, Z. and Sutton, J. (2014) ‘Qualitative research: getting started.’, *The Canadian journal of hospital pharmacy*. Canadian Society Of Hospital Pharmacists, 67(6), pp. 436–40. doi: 10.4212/cjhp.v67i6.1406.

Avrahami, D. and Hudson, S. (2002) ‘Forming interactivity: a tool for rapid prototyping of physical interactive products’, *… of the 4th conference on Designing interactive …*, p. 141. doi: http://doi.acm.org/10.1145/778712.778735.

Aypay, Ayşe *et al.* (2012) ‘Technology acceptance in education: A study of pre-service teachers in Turkey’, *Turkish Online Journal of Educational Technology*, 11(4), pp. 264–272.

Azevedo, R. *et al.* (2011) ‘Adaptive content and process scaffolding: A key to facilitating students’ self-regulated learning with hypermedia’, *Psychological Testing and Assessment Modeling*, 53(1), pp. 106–140.

Azizinezhad, M. and Hashemi, M. (2011) ‘Technology as a medium for applying constructivist teaching methods and inspiring kids’, in *Procedia - Social and Behavioral Sciences*. Elsevier, pp. 862–866. doi: 10.1016/j.sbspro.2011.11.158.

Babbie, E. R. and Mouton, J. (Johann) (2001) *The practice of social research*. Oxford University Press Southern Africa.

Bacharach, S. B. (1989) ‘Organizational Theories: Some Criteria for Evaluation.’, *Academy of Management Review*, 14(4), pp. 496–515. doi: 10.5465/AMR.1989.4308374.

Baddeley, A. (2003) ‘Working memory: Looking back and looking forward’, *Nature*

Reviews Neuroscience, 4(10), pp. 829–839. doi: 10.1038/nrn1201.

Baddeley, A. D. (2017) 'Working memory: Theories, models, and controversies', in *Exploring Working Memory: Selected works of Alan Baddeley*, pp. 333–369. doi: 10.4324/9781315111261.

Bagozzi, R. P. and Yi, Y. (1988) 'On the Evaluation of Structural Equation Models', *Journal of the Academy of Marketing Science*, pp. 74–94. doi: 10.1177/009207038801600107.

Bakker, S. and Niemantsverdriet, K. (2016) 'The interaction-attention continuum: Considering various levels of human attention in interaction design', *International Journal of Design*, 10(2), pp. 1–14.

Balog, A. and Pribeanu, C. (2016) 'An Extended Acceptance Model for Augmented Reality Educational Applications', in Neto, F. M. M., de Souza, R., and Gomes, A. S. (eds) *Handbook of Research on 3-D Virtual Environments and Hypermedia for Ubiquitous Learning*, pp. 537–554. doi: 10.4018/978-1-5225-0125-1.

Bandura, Alfred (1977) 'Self-efficacy: Toward a Unifiying Theory of Behavioural Change', *Psychological Review*, 84(2), pp. 191–215.

Bandura, Albert (1977) 'Social learning theory', in *Social Learning Theory*, pp. 1–46. doi: 10.1111/j.1460-2466.1978.tb01621.x.

Bandura, A. (1982) 'Self-efficacy mechanism in human agency', *American Psychologist*, 37(2), pp. 122–147. doi: 10.1037/0003-066X.37.2.122.

Bandura, A. (1986) *Social foundations of thought and action: A social cognitive theory*, *PrenticeHall series in social learning theory*.

Banica, L. (2014) 'Different Hype Cycle Viewpoints for an E-Learning System', *IOSR Journal of Research & Method in Education (IOSRJRME)*, 4(5), pp. 88–95. doi: 10.9790/7388-04528895.

Barajas, A. O., Al Osman, H. and Shirmohammadi, S. (2017) 'A Serious Game for children with Autism Spectrum Disorder as a tool for play therapy', in *2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH)*. IEEE, pp. 1–7. doi: 10.1109/SeGAH.2017.7939266.

Barker, P. and Phil (2008) ‘Animated visual models to enhance student understanding of complex processes’. © Higher Education Academy Engineering Subject Centre, Loughborough University.

Barneva, R. P. *et al.* (2018) ‘Tangible Technology-Enhanced Learning for Improvement of Student Collaboration’, *Journal of Educational Technology Systems*. SAGE PublicationsSage CA: Los Angeles, CA, 46(3), pp. 284–302. doi: 10.1177/0047239517736875.

Barry, B. a (2000) ‘Story Beads: a wearable for distributed and mobile storytelling’, *Mit*, pp. 1–69.

Baskerville, R. and Pries-Heje, J. (2010) ‘Explanatory Design Theory’, *Business & Information Systems Engineering*, 2(5), pp. 271–282. doi: 10.1007/s12599-010-0118-4.

Baturay, M. H., Gökçearslan, Ş. and Ke, F. (2017) ‘The relationship among pre-service teachers computer competence, attitude towards computer-assisted education, and intention of technology acceptance’, *International Journal of Technology Enhanced Learning*, 9(1), pp. 1–13. doi: 10.1504/IJTEL.2017.10003119.

Bdeir, A. (2009) ‘Electronics as material: littleBits’, in *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction - TEI ’09*, p. 397. doi: 10.1145/1517664.1517743.

Beach, L. R. and Mitchell, T. (1998) ‘The Basics of Image Theory’, in *Image Theory: Theoretical and Empirical Foundations*, pp. 3–18.

Beach, L. R. and Mitchell, T. R. (1996) ‘Image Theory, the Unifying Perspective’, in *Decision Making in the Workplace: A Unified Perspective*, pp. 1–20.

Beattie, G. *et al.* (2006) ‘Hand on What: An experimental investigation of some properties of individual iconic ...’, *Cognition*, 43(2), pp. 1086–1109. doi: 10.1002/tea.

Beaudouin-Lafon, M. (2000) ‘Instrumental interaction: An Interaction Model for Designing Post-WIMP User Interfaces’, *Proceedings of the 18th international conference on Human factors in computing systems - CHI ’00*, 2(1), pp. 446–453. doi: 10.1145/332040.332473.

Beaudry, A. and Pinsonneault, A. (2005) 'Understanding User Responses to Information Technology: A Coping Model of User Adaptation', *MIS Quarterly*, 29(3), pp. 493–524. doi: Article.

Bedwell, M., Hancell, P. J. and Callus, K. J. (1984) 'Queuing Theory And Computer Simulation For Engineering Undergraduate Courses', in *UKSC Conference on Computer Simulation*. Elsevier, pp. 434–441. doi: 10.1016/B978-0-408-01504-2.50046-6.

Bedy, M. J. *et al.* (1999) 'Design and construction of a user-level kernel for teaching multithreaded programming', in *Frontiers in Education Conference*. Puerto Rico, pp. 13a3-24-13a3-29. doi: 10.1109/FIE.1999.841728.

Beetham, H. and Sharpe, R. (2013) *Rethinking pedagogy for a digital age: designing for 21st century learning*. Routledge.

Bencina, R. and Kaltenbrunner, M. (2005) 'The Design and Evolution of Fiducials for the reacTIVision System', in *Proc. 3rd International Conference on Generative Systems in the Electronic Arts*. Melbourne, Australia.

Benford, S. *et al.* (2005) 'Expected, sensed, and desired: A framework for designing sensing-based interaction', *ACM Transactions on Computer-Human Interaction (TOCHI)*, 12(1), pp. 3–30. doi: 10.1145/1057237.1057239.

Benitti, F. B. V. (2012) 'Exploring the educational potential of robotics in schools: A systematic review', *Computers and Education*, pp. 978–988. doi: 10.1016/j.compedu.2011.10.006.

Bennett, S., Maton, K. and Carrington, L. (2011) 'Understanding the complexity of technology acceptance by higher education students', *Technology Acceptance in Education: Research and Issues*. Edited by T. Teo, pp. 63–77.

Berry, J. W. (1990) 'Imposed etics, emics, and derived etics: their conceptual and operational status in cross-cultural psychology', in *Emics and etics: the insider/outsider debate*.

Berry, W. (2008) 'Surviving Lecture: A Pedagogical Alternative', *College Teaching*. Heldref, 56(3), pp. 149–153. doi: 10.3200/CTCH.56.3.149-153.

Bers, M. U. and Portsmore, M. (2005) 'Teaching partnerships: Early childhood and engineering students teaching math and science through robotics', *Journal of Science Education and Technology*, 14(1), pp. 59–73. doi: 10.1007/s10956-005-2734-1.

Bhat, U. N. (2014) *An Introduction to Queueing Theory Modeling and Analysis in Applications*, *Igarss 2014*. doi: 10.1007/s13398-014-0173-7.2.

Bi, Y. and Beidler, J. (2007) 'A Visual Tool for Teaching Multithreading in Java', *J. Comput. Sci. Coll.*, 22(6), pp. 156–163.

Billinghurst, M., Kato, H. and Myojin, S. (2009) 'Advanced Interaction Techniques for Augmented Reality Applications', *Third International Conference on Virtual and Mixed Reality*, 5622 LNCS, pp. 13–22. doi: 10.1007/978-3-642-02771-0_2.

Billinghurst, M., Kato, H. and Poupyrev, I. (2008) 'Tangible augmented reality', in *ACM SIGGRAPH ASIA 2008 courses on - SIGGRAPH Asia '08*, pp. 1–10. doi: 10.1145/1508044.1508051.

Blasco-Arcas, L. *et al.* (2013) 'Using clickers in class. the role of interactivity, active collaborative learning and engagement in learning performance', *Computers and Education*. Pergamon, 62, pp. 102–110. doi: 10.1016/j.compedu.2012.10.019.

Bockholt, M. and Anna, K. (2015) 'Why is this so hard? Insights from the state space of a simple board game', in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, pp. 147–157. doi: 10.1007/978-3-319-19126-3_13.

Boden, A. *et al.* (2014) 'Tangible and screen-based interfaces for end-user workflow modeling', *IEEE Software*, 31(4), pp. 65–71. doi: 10.1109/MS.2013.71.

Bodin, E. V and Ershov, A. P. (2013) 'Spin for puzzles: Using Spin for solving the Japanese river puzzle and the Square-1 cube', *System Informatics*, (2).

Borghi, A. M. *et al.* (2017) 'The challenge of abstract concepts', *Psychological Bulletin*, 143(3), pp. 263–292. doi: 10.1037/bul0000089.

Borovoy, R. *et al.* (1996) 'Things that blink: Computationally augmented name tags', *IBM Systems Journal*, 35(3.4), pp. 488–495. doi: 10.1147/sj.353.0488.

Bottino, A. *et al.* (2016) 'GAINE - A portable framework for the development of edutainment applications based on multitouch and tangible interaction', *Entertainment Computing*, 16, pp. 53–65. doi: 10.1016/j.entcom.2016.04.001.

Bottino, A., Martina, A. and Toosi, A. (2015) 'GAINE — tanGible augmented interaction for edutainment', *Intelligent Technologies for Interactive Entertainment (INTETAIN), 2015 7th International Conference on*, 17, pp. 207–216. doi: 10.4108/icst.intetain.2015.259627.

Boudreau, M.-C. and Robey, D. (2005) 'Enacting integrated information technology: A human agency perspective', *Organization Science*, 16(1), pp. 3–18. doi: 10.1287/orsc.1040.0103.

Boumediene, R. and Kawalek, P. (2008) 'Predicting SMEs Willingness to Adopt ERP, CRM, SCM & E-Procurement Systems', *16th European Conference on Information Systems, ECIS 2008*, pp. 961–973. doi: 10.1108/17410390910922796.

Bower, M. (2006) 'Virtual classroom pedagogy', *ACM SIGCSE Bulletin*, 38, p. 148. doi: 10.1145/1124706.1121390.

Brannick, T. and Coghlan, D. (2007) 'In Defense of Being "Native": The Case for Insider Academic Research', *Organizational Research Methods*. Sage PublicationsSage CA: Thousand Oaks, CA, 10(1), pp. 59–74. doi: 10.1177/1094428106289253.

Bransford, J. D. and Schwartz, D. L. (1999) 'Rethinking Transfer: A Simple Proposal with Multiple Implications', *Source: Review of Research in Education*, 24154112(1999), pp. 61–100. doi: 10.3102/0091732X024001061.

Braspenning, P. J., Thuijsman, F. and Weijters, A. (1995) *Artificial neural networks: an introduction to ANN theory and practice*. 931st edn, *Psicothema*. 931st edn. Springer Science & Business Media.

Brezavšček, A., Šparl, P. and Žnidaršič, A. (2014) 'Extended Technology Acceptance Model for SPSS Acceptance among Slovenian Students of Social Sciences', *Organizacija*, 47(2). doi: 10.2478/orga-2014-0009.

Brooke, J. (1996) 'SUS - A quick and dirty usability scale', *Usability evaluation in* *industry*, 189(194), pp. 4–7. doi: 10.1002/hbm.20701.

Buitinck, L. *et al.* (2013) 'API design for machine learning software: experiences from the scikit-learn project'.

Bumbacher, E. *et al.* (2013) 'BeatTable', in *Proceedings of the 12th International Conference on Interaction Design and Children - IDC '13*. New York, New York, USA: ACM Press, pp. 589–592. doi: 10.1145/2485760.2485872.

Bürdek, B. E. (2005) *Design: history, theory and practice of product design*, *Design History Theory and Practice of Product Design*. doi: 10.1007/3-7643-7681-3_2.

Burns, A. (2006) *Integrating research and professional development on pronunciation teaching in a national adult ESL program*. Austrialia.

Burton-Jones, A. and Hubona, G. S. (2006) 'The mediation of external variables in the technology acceptance model', *Information and Management*. North-Holland, 43(6), pp. 706–717. doi: 10.1016/j.im.2006.03.007.

Bush, M. D., Terry, R. M. and Languages, A. C. on the T. of F. (1997) *Technology-enhanced language learning*, *The ACTFL foreign language education series*.

Butterfield, A. *et al.* (2004) 'PyEvolve: a toolkit for statistical modelling of molecular evolution', *BMC Bioinformatics*. BioMed Central, 5(1), p. 1. doi: 10.1186/1471-2105-5-1.

Calhoun Williams, K. J. (2017) 'Hype Cycle for Education, 2017', *Gartner Research*, (July), p. 89. doi: G00313670.

Camarata, K. *et al.* (2002) 'Navigational blocks: navigating information space with tangible media', *International Conference on Intelligent User Interfaces*, pp. 31–38. doi: 10.1145/502716.502725.

Camilleri, M. A. and Camilleri, A. C. (2017) 'Digital Learning Resources and Ubiquitous Technologies in Education', *Technology, Knowledge and Learning*. Springer Netherlands, 22(1), pp. 65–82. doi: 10.1007/s10758-016-9287-7.

Cassell, J. (2004) 'Towards a model of technology and literacy development: Story listening systems', *Journal of Applied Developmental Psychology*, 25(1), pp. 75–105.

doi: 10.1016/j.appdev.2003.11.003.

Cassidy, S. (2004) 'Learning styles: An overview of theories, models, and measures', *Educational Psychology*, pp. 419–444. doi: 10.1080/0144341042000228834.

Castañeda, J. A., Muñoz-Leiva, F. and Luque, T. (2007) 'Web Acceptance Model (WAM): Moderating effects of user experience', *Information and Management*, 44(4), pp. 384–396. doi: 10.1016/j.im.2007.02.003.

Catala, A. *et al.* (2011) 'AGORAS: Exploring creative learning on tangible user interfaces', in *Proceedings - International Computer Software and Applications Conference*, pp. 326–335. doi: 10.1109/COMPSAC.2011.50.

Caudill and Maureen (1986) 'Neural networks primer, part I', *AI Expert*. [CL Publications], 2(12), pp. 46–52.

Ceccarelli, M. (2003) 'Robotic teachers' assistants - Low cost robots for research and teaching activities', *IEEE Robotics & Automation Magazine*, 10(3), pp. 37–45.

Champoux, B. and Subramanian, S. (2004) 'A Design Approach for Tangible User Interfaces', *Australasian Journal of Information Systems*, 11(2), pp. 36–51.

Chan, S. and Lu, M. (2004) 'Understanding internet banking adoption and use behavior: A Hong Kong perspective', *Journal of Global Information Management*, 12(3), pp. 21–43. doi: Article.

Chan, Y. Y. (2007) 'Teaching queueing theory with an inquiry-based learning approach: A case for applying WebQuest in a course in simulation and statistical analysis', in *Frontiers in Education Conference, FIE*. doi: 10.1109/FIE.2007.4418162.

Chandrasekera, T. and Yoon, S.-Y. (2015) 'The Effect of Tangible User Interfaces on Cognitive Load in the Creative Design Process', *Proceedings of the 2015 IEEE International Symposium on Mixed and Augmented Reality - Media, Art, Social Science, Humanities and Design*, pp. 6–8. doi: 10.1109/ISMAR-MASH'D.2015.18.

Chang, C. W. *et al.* (2010) 'Improving the authentic learning experience by integrating robots into the mixed-reality environment', *Computers and Education*. Elsevier Ltd, 55(4), pp. 1572–1578. doi: 10.1016/j.compedu.2010.06.023.

Chau, P. Y. K. and Hu, P. J. H. (2002) 'Investigating healthcare professionals' decisions to accept telemedicine technology: An empirical test of competing theories', *Information and Management*, 39(4), pp. 297–311. doi: 10.1016/S0378-7206(01)00098-2.

Chawla, K. *et al.* (2013) 'Dr. Wagon: A "stretchable" toolkit for tangible computer programming', *ACM International Conference Proceeding Series*, pp. 561–564. doi: 10.1145/2485760.2485865.

Chen, W.-K. and Cheng, Y. C. (2007) 'Teaching Object-Oriented Programming Laboratory With Computer Game Programming', *IEEE Transactions on Education*, 50(3), pp. 197–203. doi: 10.1109/TE.2007.900026.

Cheng, Y. (2012) 'Effects of quality antecedents on e-learning acceptance', *Internet Research*, 22(3), pp. 361–390. doi: 10.1108/10662241211235699.

Cheng, Y. M. (2011) 'Antecedents and consequences of e-learning acceptance', *Information Systems Journal*, 21(3), pp. 269–299. doi: 10.1111/j.1365-2575.2010.00356.x.

Cheung, R. and Vogel, D. (2013) 'Predicting user acceptance of collaborative technologies: An extension of the technology acceptance model for e-learning', *Computers and Education*, 63, pp. 160–175. doi: 10.1016/j.compedu.2012.12.003.

Cheung, W. and Huang, W. (2005) 'Proposing a framework to assess Internet usage in university education: An empirical investigation from a student's perspective', *British Journal of Educational Technology*. Blackwell Publishing Ltd., 36(2), pp. 237–253. doi: 10.1111/j.1467-8535.2005.00455.x.

Chi, M. T. H. (2005) 'Commonsense Conceptions of Emergent Processes: Why Some Misconceptions are Robust', *The Journal of the Learning Sciences*, 14(2), pp. 161–199. doi: 10.1207/s15327809jls1402.

Chipman, G. *et al.* (2006) 'A case study of Tangible Flags: A collaborative technology to enhance field trips', in *Interaction Design and Children*, pp. 1–8. doi: 10.1145/1139073.1139081.

Chuttur, M. (2009) 'Overview of the Technology Acceptance Model: Origins , Developments and Future Directions', *Sprouts: Working Papers on Information Systems*, 9(2009), pp. 1–23. doi: 10.1021/jf001443p.

Clements, D. H. (1999) 'The Future of Educational Computing Research : The Case of Computer Programming', *Information Technology in Childhood Education*, pp. 147–179.

Clements, D. H. (2000) '"Concrete" Manipulatives, Concrete Ideas', *Contemporary Issues in Early Childhood*. SAGE PublicationsSage UK: London, England, 1(1), pp. 45–60. doi: 10.2304/ciec.2000.1.1.7.

Coffield, F. *et al.* (2004) 'Learning styles and pedagogy in post-16 learning A systematic and critical review', *Learning and Skills Research Centre*, p. 84. doi: 10.1016/S0022-5371(81)90483-7.

Cohen, D. S. (2005) 'Why Change Is an Affair of the Heart', *CIO*, 19(5), pp. 48–52.

Cohen, J. *et al.* (1999) 'Logjam: a Tangible Multi-Person Interface for Video Logging', *Chi*, pp. 128–135. doi: 10.1145/302979.303013.

Colakoglu, O. M. and Akdemir, O. (2010) 'Motivational measure of the instruction compared: Instruction based on the ARCS Motivation Theory V.S. traditional instruction in blended courses', *Turkish Online Journal of Distance Education*, 11(2), pp. 73–89. doi: Article.

Colella, V. (2000) 'Participatory Simulations: Building Collaborative Understanding Through Immersive Dynamic Modeling', *The Journal of the Learning Sciences*, 9(4), pp. 471–500. doi: 10.1207/S15327809JLS0904.

Colella, V., Borovoy, R. and Resnick, M. (1998) 'Participatory simulations: using computational objects to learn about dynamic systems', *CHI 98 Cconference Summary on Human Factors in Computing Systems*. New York, New York, USA: ACM Press, pp. 9–10. doi: 10.1145/286498.286503.

Compeau, D. and Higgins, C. (1995) 'Application of social cognitive theory to training for computer skills', *Information systems research*, 6(2), pp. 118–143. doi: 10.1287/isre.6.2.118.

Connolly, T. M. and Begg, C. E. (2006) 'A Constructivist-Based Approach to Teaching

Database Analysis and Design', *Journal of Information Systems Education*, 17(1), pp. 43–53.

Conole, G. *et al.* (2004) 'Mapping pedagogy and tools for effective learning design', in *Computers and Education*, pp. 17–33. doi: 10.1016/j.compedu.2003.12.018.

Cooper, R. B. and Zmud, R. W. (1990) 'Information Technology Implementation Research: A Technological Diffusion Approach', *Management Science*, 36(2), pp. 123–139. doi: 10.1287/mnsc.36.2.123.

Couture, N., Rivière, G. and Reuter, P. (2008) 'GeoTUI: a tangible user interface for geoscience', *Tei '08*, pp. 89–96. doi: 10.1145/1347390.1347411.

Cowan, N. (2014) 'Working Memory Underpins Cognitive Development, Learning, and Education', *Educational Psychology Review*, pp. 197–223. doi: 10.1007/s10648-013-9246-y.

Cramer, E. M. and Bock, R. D. (1966) 'Multivariate analysis', *Review of Educational Research*. Sage PublicationsSage CA: Thousand Oaks, CA, 36(5), pp. 604–617. doi: 10.3102/00346543036005604.

Crampton-Smith, G. (1995) 'The hand that rocks the cradle', *I.D*, pp. 60–65.

Creswell, J. W. (2014) *Research design : qualitative, quantitative, and mixed methods approaches*. SAGE Publications.

Cronjé, J. (2006) 'Paradigms regained: Toward integrating objectivism and constructivism in instructional design and the learning sciences', *Educational Technology Research and Development*, pp. 387–416. doi: 10.1007/s11423-006-9605-1.

Cubero, S. N. (2015) 'A fun and effective self-learning approach to teaching microcontrollers and mobile robotics', *International Journal of Electrical Engineering Education*, 52(4), pp. 298–319.

Cuendet, S. *et al.* (2015) 'An integrated way of using a tangible user interface in a classroom', *International Journal of Computer-Supported Collaborative Learning*. Springer US, 10(2), pp. 183–208. doi: 10.1007/s11412-015-9213-3.

Cuendet, S., Bumbacher, E. and Dillenbourg, P. (2012) ‘Tangible vs. virtual representations: when tangibles benefit the training of spatial skills’, in *Proceedings of the 7th Nordic Conference on Human-Computer Interaction Making Sense Through Design - NordiCHI ’12*. New York, New York, USA: ACM Press, p. 99. doi: 10.1145/2399016.2399032.

Cuendet, S. and Dillenbourg, P. (2013) ‘The Benefits and Limitations of Distributing a Tangible Interface in a Classroom’, in *10th International Conference on Computer-Supported Collaborative Learning, CSCL*, pp. 137–144.

Cvetanovic, M. *et al.* (2011) ‘ADVICE—Educational System for Teaching Database Courses’, *IEEE Transactions on Education*, 54(3), pp. 398–409. doi: 10.1109/TE.2010.2063431.

Cypher, A. *et al.* (1993) ‘Watch what I do : programming by demonstration’. MIT Press, p. 652.

Czenky, M. (2014) ‘The Efficiency Examination Of Teaching Of Different Normalization Methods’, *International Journal of Database Management Systems*, 6(2), pp. 1–18. doi: 10.5121/ijdms.2014.6201.

Dabbagh, N. *et al.* (2016) ‘Evolution of Learning Technologies: Past, Present, and Future’, in. Springer, Cham, pp. 1–7. doi: 10.1007/978-3-319-22963-8_1.

Dalsgaard, P. and Halskov, K. (2012) ‘Tangible 3D Tabletops: Combining Tangible Tabletop Interaction and 3D Projection’, *Proceedings of the 7th Nordic Conference on Human-Computer Interaction Making Sense Through Design - NordiCHI ’12*, p. 109. doi: 10.1145/2399016.2399033.

Davis, F., Bagozzi, R. and Warshaw, W. (1989) ‘User acceptance of computer technology: A comparison of two theoretical models’, *Management Science*, 35(8), pp. 982–1003. doi: 10.1287/mnsc.35.8.982.

Davis, F. D. (1986) *A technology acceptance model for empirically testing new end-user information systems: Theory and results*, *Management*. doi: oclc/56932490.

Davis, F. D. (1989) ‘Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology’, *MIS Quarterly*, 13(3), p. 319. doi:

10.2307/249008.

Davis, F. D. (1993) ‘User acceptance of information technology: system characteristics, user perceptions and behavioral impacts’, *International Journal of Man-Machine Studies*. Academic Press, 38(3), pp. 475–487. doi: 10.1006/imms.1993.1022.

Day, J. A. and Foley, J. D. (2006) ‘Evaluating a web lecture intervention in a human-computer interaction course’, *IEEE Transactions on Education*, 49(4), pp. 420–431. doi: 10.1109/TE.2006.879792.

Dečman, M. (2015) ‘Modeling the acceptance of e-learning in mandatory environments of higher education: The influence of previous education and gender’, *Computers in Human Behavior*. Pergamon, 49, pp. 272–281. doi: 10.1016/j.chb.2015.03.022.

Dede, C. *et al.* (1999) ‘Multisensory immersion as a modeling environment for learning complex scientific concepts’, *Modeling and simulation in science and mathematics education*. Springer-Verlag, pp. 282–319.

DeLone, W. H. and Mclean, E. R. (2003) ‘The DeLone and McLean Model of Information Systems Success: A Ten-Year Update’, *Journal of Management Information Systems / Spring*, 19(4), pp. 9–30. doi: 10.1073/pnas.0914199107.

DeNero, J. and Klein, D. (2010) ‘Teaching introductory artificial intelligence with pac-man’, *Proceedings of the Symposium on Educational Advances in Artificial Intelligence*, pp. 1885–1889.

Deng, J. D. and Purvis, M. K. (2015) ‘Teaching service modelling to a mixed class: An integrated approach’, *Informatics in Education*, 14(1), pp. 37–52. doi: 10.15388/infedu.2015.03.

Dennis, A. R. *et al.* (1997) ‘Research Report: The Effectiveness of Multiple Dialogues in Electronic Brainstorming’, *Information Systems Research*, 8(2), pp. 203–211. doi: 10.1287/isre.8.2.203.

Dennis, A. R. and Valacich, J. S. (1993) ‘Computer Brainstorms: More Heads Are Better Than One’, *Journal of Applied Psychology*, 78(4), pp. 531–537. doi:

10.1037/0021-9010.78.4.531.

Denzin, N. K. and Lincoln, Y. S. (2008) *The landscape of qualitative research: Theories and Issues*. 2nd Editio, *Handbook of qualitative research*. 2nd Editio. London: SAGE PublicationsSage UK: London, England. doi: 10.1177/1094428109332198.

Denzin, N. K. and Lincoln, Y. S. (2017) *The SAGE handbook of qualitative research*.

Devi, S. and Deb, S. (2017) ‘Exploring the potential of tangible user interface in classroom teaching — Learning’, in *2017 3rd International Conference on Computational Intelligence & Communication Technology (CICT)*. IEEE, pp. 1–7. doi: 10.1109/CIACT.2017.7977368.

Díaz-Moreno, P. *et al.* (2016) ‘Educational Software Based on Matlab GUIs for Neural Networks Courses’, in *Handbook of Research on Computational Simulation and Modeling in Engineering*, pp. 333–358. doi: 10.4018/978-1-5225-0159-6.ch075.

Dishaw, M. T. and Strong, D. M. (1999) ‘Extending the technology acceptance model with task-technology fit constructs’, *Information & Management*, 36(1), pp. 9–21.

Dongare, Y. V., Dhabe, P. S. and Deshmukh, S. V. (2011) ‘RDBNorma: - A semi-automated tool for relational database schema normalization up to third normal form’, *International Journal of Database Management Systems (IJDMS)*, 3(1), pp. 133–154. doi: 10.5121/ijdms.2011.3109.

Dourish, P. (2001) ‘Where the Action Is: The Foundations of Embodied Interaction’, *Where the action is the foundations of embodied interaction*, p. chaper 1-3. doi: 10.1162/leon.2003.36.5.412.

Drago, W. A. and Wagner, R. J. (2004) ‘Vark preferred learning styles and online education’, *Management Research News*, 27(7), pp. 1–13. doi: 10.1108/01409170410784211.

Dumpit, D. Z. and Fernandez, C. J. (2017) ‘Analysis of the use of social media in Higher Education Institutions (HEIs) using the Technology Acceptance Model’, *International Journal of Educational Technology in Higher Education*. Nature Publishing Group, 14(1), p. 5. doi: 10.1186/s41239-017-0045-2.

Dyne, M. Van and Fjermestad, J. (2012) ‘Robotics in education: a tool for recruiting, engaging, retaining and educating students', *Proceedings of the 12th WSEAS International Conference on Robotics, Control and Manufacturing Technology (ROCOM '12)*, pp. 196–201.

Edge, D. and Blackwell, A. (2006) 'Correlates of the cognitive dimensions for tangible user interface', *Journal of Visual Languages and Computing*, 17(4), pp. 366–394. doi: 10.1016/j.jvlc.2006.04.005.

Eguchi, A. (2014) 'Robotics as a Learning Tool for Educational Transformation', *International Workshop Teaching Robotics, Teaching with Robotics & International Conference Robotics in Education*, pp. 27–34. doi: 10.4018/978-1-4666-8363-1.ch002.

Eom, D. S. *et al.* (2008) 'A multi-player arcade video game platform with a wireless tangible user interface', *IEEE Transactions on Consumer Electronics*, 54(4), pp. 1819–1824. doi: 10.1109/TCE.2008.4711240.

Eom, S. B., Ashill, N. and Wen, H. (2006) 'The Determinants of Students' Perceived Learning Outcomes and Satisfaction in University Online Education: An Empirical Investigation.', *Decision Sciences Journal of Innovative Education*, 14(2), pp. 185–215. doi: 10.1111/j.1540-4609.2006.00114.x.

Ernesto, S. (2002) 'Teachers beliefs about usefulness of simulation with the educational software fathom for developing probability concepts in statistics classroom', in *The Sixth International Conference on Teaching Statistics*, pp. 1–6.

Ertl, B. (2010) 'Technologies and practices for constructing knowledge in online environments : advancements in learning'. Information Science Reference, p. 261.

Escobar-Rodriguez, T. and Monge-Lozano, P. (2012) 'The acceptance of Moodle technology by business administration students', *Computers and Education*, 58(4), pp. 1085–1093. doi: 10.1016/j.compedu.2011.11.012.

Esteban-Millat, I. *et al.* (2018) 'An extension of the technology acceptance model for online learning environments', *Interactive Learning Environments*. Routledge, pp. 1–16. doi: 10.1080/10494820.2017.1421560.

Esteves, A. and Oakley, I. (2011) 'Design for interface consistency or embodied facilitation?', in *CHI 2011 Embodied Interaction: Theory and Practice in HCI Workshop*, pp. 1–4.

Fan, M. *et al.* (2014) 'Exploring how a co-dependent tangible tool design supports collaboration in a tabletop activity', in *Proceedings of the 18th International Conference on Supporting Group Work (GROUP '14)*, pp. 81–90. doi: 10.1145/2660398.2660402.

Fan, M., Antle, A. N. and Sarker, S. (2018) 'From Tangible to Augmented', in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. New York, New York, USA: ACM Press, pp. 1–6. doi: 10.1145/3170427.3188459.

Farahat, T. (2012) 'Applying the Technology Acceptance Model to Online Learning in the Egyptian Universities', *Procedia - Social and Behavioral Sciences*, 64, pp. 95–104. doi: 10.1016/j.sbspro.2012.11.012.

Farr, W., Yuill, N. and Raffle, H. (2010) 'Social benefits of a tangible user interface for children with Autistic Spectrum Conditions.', *Autism : the international journal of research and practice*, 14(3), pp. 237–252. doi: 10.1177/1362361310363280.

Fathema, N., Shannon, D. and Ross, M. (2015) 'Expanding The Technology Acceptance Model (TAM) to Examine Faculty Use of Learning Management Systems (LMSs) In Higher Education Institutions', *MERLOT Journal of Online Learning and Teaching*, 11(2), pp. 210–232. doi: 10.12720/joams.4.2.92-97.

Fayad, R. and Paper, D. (2015) 'The Technology Acceptance Model E-Commerce Extension: A Conceptual Framework', *Procedia Economics and Finance*, 26, pp. 1000–1006. doi: 10.1016/S2212-5671(15)00922-3.

Felder, R. M. *et al.* (2000) 'The Future of Engineering Education II. Teaching methods that work', *Chem. Engr. Education*, 34(1), pp. 26–39. doi: 10.1.1.34.1082.

Felder, R. and Silverman, L. (1988) 'Learning and teaching styles in engineering education', *Engineering education*, 78(June), pp. 674–681. doi: 10.1109/FIE.2008.4720326.

Fernaeus, Y. and Tholander, J. (2006) 'Finding design qualities in a tangible programming space', in *Proceedings of the SIGCHI conference on Human Factors in computing systems CHI 06*. New York, New York, USA: ACM Press, p. 447. doi:

10.1145/1124772.1124839.

Fernando, R., Dupre, K. and Skates, H. (2016) ‘Tangible user interfaces for teaching building physics: Towards continuous designing in education’, in *CAADRIA 2016, 21st International Conference on Computer-Aided Architectural Design Research in Asia - Living Systems and Micro-Utopias: Towards Continuous Designing*. Melbourne, Australia, pp. 693–702.

Fiorentino, M., Monno, G. and E., A. (2010) ‘Tangible Interfaces for Augmented Engineering Data Management’, in *Augmented Reality*. InTech. doi: 10.5772/7130.

Fishbein, M. and Ajzen, I. (1975) ‘Belief, Attitude, Intention and Behaviour: An Introduction to Theory and Research’, *Reading MA AddisonWesley*, (August), p. 480. doi: 10.2307/2065853.

Fishkin, K. P. (2004) ‘A taxonomy for and analysis of tangible interfaces’, *Personal and Ubiquitous Computing*, 8(5), pp. 347–358. doi: 10.1007/s00779-004-0297-4.

Fitzgerald, S. and Place, J. (1995) ‘Teaching elementary queueing theory with a computer algebra system’, *ACM SIGCSE Bulletin*. ACM, 27(1), pp. 350–354. doi: 10.1145/199691.199857.

Fitzmaurice, G. W. (1996) ‘Graspable user interfaces’, *Citeseer*, p. 167. doi: 10.1.1.120.2035.

Fitzmaurice, G. W. and Buxton, W. (1997) ‘An empirical evaluation of graspable user interfaces: towards specialized, space-multiplexed input’, *Proceedings of the SIGCHI conference on Human factors in computing systems*, (1), pp. 43–50. doi: 10.1145/258549.258578.

Fitzmaurice, G. W., Ishii, H. and Buxton, W. a. S. (1995) ‘Bricks: laying the foundations for graspable user interfaces’, in *SIGCHI Conference on Human Factors in Computing Systems*. New York, New York, USA: ACM Press, pp. 442–449. doi: 10.1145/223904.223964.

Fjeld, M. *et al.* (2004) ‘Teaching electronegativity and dipole moment in a TUI’, in *Proceedings - IEEE International Conference on Advanced Learning Technologies, ICALT 2004*, pp. 792–794. doi: 10.1109/ICALT.2004.1357659.

Fjeld, M. *et al.* (2007) 'Tangible user interface for chemistry education: comparative evaluation and re-design', in *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 805–808. doi: 10.1145/1240624.1240745.

Fjeld, M. and Barendregt, W. (2009) 'Epistemic action: A measure for cognitive support in tangible user interfaces?', *Behavior Research Methods*. Springer-Verlag, 41(3), pp. 876–881. doi: 10.3758/BRM.41.3.876.

Fjeld, M. and Voegtli, B. M. (2002) 'Augmented Chemistry: An interactive educational workbench', in *Proceedings - International Symposium on Mixed and Augmented Reality, ISMAR 2002*, pp. 259–260. doi: 10.1109/ISMAR.2002.1115100.

Fleming, N. and Baume, D. (2006) 'Learning Styles Again: VARKing up the right tree!', *Educational Developments*, 7(4), pp. 4–7.

Fleming, N. D. and Mills, C. (1992) 'Not another inventory, rather a catalyst for reflection', *To improve the academy*, 11(1), p. 137.

Fogg, B. (2009) 'A behavior model for persuasive design', in *Proceedings of the 4th International Conference on Persuasive Technology - Persuasive*, pp. 40–46. doi: 10.1145/1541948.1541999.

Fontijn, W. and Hoonhout, J. (2007) 'Functional fun with tangible user interfaces', in *Proceedings - DIGITEL 2007: First IEEE International Workshop on Digital Game and Intelligent Toy Enhanced Learning*, pp. 119–123. doi: 10.1109/DIGITEL.2007.26.

Fowler, A., Fristce, T. and Maclauren, M. (2012) 'Kodu Game Lab: a programming environment', *The Computer Games Journal*, 1(1), pp. 17–28.

Fox, M. F. (2015) 'Gender and Clarity of Evaluation among Academic Scientists in Research Universities', *Science Technology and Human Values*. SAGE PublicationsSage CA: Los Angeles, CA, 40(4), pp. 487–515. doi: 10.1177/0162243914564074.

Fox, N. J. (2008) 'Post-Positivism', in Given, L. M. (ed.) *The Sage Encyclopedia of Qualitative Research Methods*. Volumes 1&. Alberta, p. 1043.

Frank, E., Hall, M. A. and Witten, I. H. (2016) 'The WEKA Workbench', *Morgan Kaufmann, Fourth Edition*, pp. 553–571.

Fraser, M. *et al.* (2003) ‘Assembling History: Achieving Coherent Experiences with Diverse Technologies’, *ECSCW 2003: Proceedings of the Eighth European Conference on Computer Supported Cooperative Work 14--18 September 2003, Helsinki, Finland*. Dordrecht: Springer Netherlands, (September), pp. 179–198. doi: 10.1007/978-94-010-0068-0_10.

Fraser, N. (2015) ‘Ten things we’ve learned from Blockly’, in *2015 IEEE Blocks and Beyond Workshop (Blocks and Beyond)*. IEEE, pp. 49–50. doi: 10.1109/BLOCKS.2015.7369000.

Frazer, J. (1995) ‘An Evolutionary Architecture’, *An Evolutionary architecture*, p. 127.

Freeman, C. and Silverman, B. G. (1993) ‘On Teaching AI and Expert Systems Courses’, *IEEE Transactions on Education*, 36(1), pp. 193–197. doi: 10.1109/13.204845.

Freeman, S. *et al.* (2014) ‘Active learning increases student performance in science, engineering, and mathematics’, *Proceedings of the National Academy of Sciences*, 111(23), pp. 8410–8415. doi: 10.1073/pnas.1319030111.

Frei, P. *et al.* (2000) ‘Curlybot: designing a new class of computational toys’, *Proceedings of the SIGCHI conference on Human factors in computing systems*, 2(1), pp. 129–136. doi: http://doi.acm.org/10.1145/332040.332416.

Friese, S. and Rother, K. (2013) ‘Teaching artificial intelligence using a web-based game server’, in *Proceedings of the 13th Koli Calling International Conference on Computing Education Research - Koli Calling ’13*. New York, New York, USA: ACM Press, pp. 193–194. doi: 10.1145/2526968.2526992.

Gaggi, O. and Regazzo, M. (2014) ‘Tactive, a framework for cross platform development of tabletop applications’, *WEBIST 2014 - Proceedings of the 10th International Conference on Web Information Systems and Technologies*, 2, pp. 91–98.

Gagné R (1970) ‘The conditions of learning’, *Science*, 1(34), p. 1993. doi: 10.1016/0022-4405(79)90058-X.

Garber, L. (2012) ‘Tangible user interfaces: Technology you can touch’, *Computer*, 45(6), pp. 15–18. doi: 10.1109/MC.2012.218.

García, J. and Hernandez, Á. (2010) ‘Active methodologies in a queueing systems course for telecommunication engineering studies’, *IEEE Transactions on Education*, 53(3), pp. 405–412. doi: 10.1109/TE.2009.2026365.

Gasparinatou, A. and Grigoriadou, M. (2011) ‘ALMA: An Adaptive Learning Models environment from texts and Activities that improves students’ science comprehension’, in *Procedia - Social and Behavioral Sciences*, pp. 2742–2747. doi: 10.1016/j.sbspro.2011.04.181.

Gee, J. P. (2011) *An introduction to discourse analysis : theory and method*. Routledge.

Gefen, D. (2004) ‘What Makes an ERP Implementation Relationship Worthwhile: Linking Trust Mechanisms and ERP Usefulness’, *Journal of Management Information Systems*, 21(1), pp. 263–288. doi: 10.1080/07421222.2004.11045792.

Gefen, D., Karahanna, E. and Straub, D. W. (2003) ‘Inexperience and experience with online stores: The importance of TAM and trust’, *IEEE Transactions on Engineering Management*, 50(3), pp. 307–321. doi: 10.1109/TEM.2003.817277.

van Gelder, T. and Clark, A. (1998) ‘Being There: Putting Brain, Body and World Together Again.’, *The Philosophical Review*, 107(4), p. 647. doi: 10.2307/2998391.

Giacaman, N. (2012) ‘Teaching by example: Using analogies and live coding demonstrations to teach parallel computing concepts to undergraduate students’, *Proceedings of the 2012 IEEE 26th International Parallel and Distributed Processing Symposium Workshops, IPDPSW 2012*, pp. 1295–1298. doi: 10.1109/IPDPSW.2012.158.

Gignac, G. E. (2009) ‘Partial confirmatory factor analysis: Described and illustrated on the NEO-PI-R’, *Journal of Personality Assessment*, 91(1), pp. 40–47. doi: 10.1080/00223890802484126.

Gillet, A. *et al.* (2004) ‘Augmented reality with tangible auto-fabricated models for molecular biology applications’, *IEEE Visualization 2004*. IEEE Comput. Soc, pp. 235–241. doi: 10.1109/VISUAL.2004.7.

Gillet, A. *et al.* (2005) 'Tangible augmented interfaces for structural molecular biology', *IEEE Computer Graphics and Applications*, 25(2), pp. 13–17. doi: 10.1109/MCG.2005.47.

Girouard, A. *et al.* (2007) 'Smart Blocks : A Tangible Mathematical Manipulative', *Proceedings of the 1st international conference on Tangible and embedded interaction*, (Figure 2), pp. 183–186. doi: 10.1145/1226969.1227007.

Gist, M. E., Schwoerer, C. and Rosen, B. (1989) 'Effects of Alternative Training Methods on Self-Efficacy and Performance in Computer Software Training', *Journal of Applied Psychology*, 74(6), pp. 884–891. doi: 10.1037/0021-9010.74.6.884.

Giuseppe, A. and Martina, P. (2012) 'Educational Robotics Between Narration and Simulation', *Procedia - Social and Behavioral Sciences*, 51, pp. 104–109. doi: 10.1016/j.sbspro.2012.08.126.

Goh, W. B. *et al.* (2012) 'The i-Cube: design considerations for block-based digital manipulatives and their applications', in *Proceedings of the Designing Interactive Systems Conference on - DIS '12*. New York, New York, USA: ACM Press, p. 398. doi: 10.1145/2317956.2318016.

Goldin-Meadow, S. (2014) 'How gesture works to change our minds', *Trends in Neuroscience and Education*, pp. 4–6. doi: 10.1016/j.tine.2014.01.002.

Goldsman, D. (2007) 'A simulation course for high school students', in *Winter Simulation Conference*, pp. 2353–2356. doi: 10.1109/WSC.2007.4419875.

Goldstein, C. *et al.* (2005) 'Using a Network Simulation Tool to engage students in Active Learning enhances their understanding of complex data communications concepts .', *the 7th Australasian conference on Computing education - Volume 42 (ACE '05)*, 42(c), pp. 223--228. doi: 10.1.1.59.2841.

Gong, M., Xu, Y. and Yu, Y. (2004) 'An Enhanced Technology Acceptance Model for Web-Based Learning', *Journal of Information Systems Education*, 15(4), pp. 365–374.

Goodfellow, I. J. *et al.* (2013) 'Pylearn2: a machine learning research library'.

Gorbet, M. G., Orth, M. and Ishii, H. (1998) 'Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography', *Proceedings of the*

SIGCHI conference on Human factors in computing systems. ACM Press/Addison-Wesley Publishing Co., pp. 1–8. doi: http://doi.acm.org/10.1145/274644.274652.

Goschnick, S. (2018) *Innovative methods, user-friendly tools, coding, and design approaches in people-oriented programming*. 1st edn. IGI Global.

Gray, D. E. (2014) *Doing Research in the Real World (3rd ed.)*, *SAGE*.

Greenberg, S. and Fitchett, C. (2001) 'Phidgets: easy development of physical interfaces through physical widgets', *Proceedings of the 14th annual ACM symposium on User interface software and technology*, 3(2), pp. 209–218. doi: 10.1145/502348.502388.

Grivokostopoulou, F. and Hatzilygeroudis, I. (2013) 'Teaching ai search algorithms in a web-based educational system', *Proceedings of the International Conference e-Learning 2013*, (Woolf 2009), pp. 83–90.

Grossman, T. A. (1999) 'Teachers' forum: Spreadsheet modeling and simulation improves understanding of queues', *Interfaces*, 29(3), pp. 88–103. doi: 10.1287/inte.29.3.88.

Grote, C. *et al.* (2015) 'Eugenie: Multi-touch and tangible interaction for bio-design', *Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction - TEI '15*, pp. 217–224. doi: 10.1145/2677199.2680605.

Groves, M. M. and Zemel, P. C. (2000) 'Instructional Technology Adoption in Higher Education: An Action Research Case Study', *International Journal of Instructional Media*, 27, pp. 57–65.

Grundy, J. and Hosking, J. (2000) 'Developing adaptable user interfaces for component-based systems', in *Proceedings - 1st Australasian User Interface Conference, AUIC 2000*, pp. 17–25. doi: 10.1109/AUIC.2000.822060.

Gu, X., Zhu, Y. and Guo, X. (2012) 'Meeting the "Digital Natives": Understanding the Acceptance of Technology in Classrooms.', *Educational Technology & Society*, 16(1), pp. 392–402. doi: 10.2307/JEDUCTECHSOCI.16.1.392.

Guan, X. *et al.* (2014) 'Study of Design Method for Tangible User Interface', (1), pp. 2055–2056.

Guest, G., Namey, E. E. and Mitchell, M. L. (2013) ‘In-depth interviews’, in *Collecting Qualitative Data: A Field Manual for Applied Research*. London: SAGE Publications, Ltd, pp. 113–171. doi: 10.4135/9781506374680.

Gulatee, Y. and Combes, B. (2006) ‘Identifying the Challenges in Teaching Computer Science Topics Online’, *EDU-COM International Conference*.

Guzmán-Valenzuela, C. (2016) ‘Connecting Theory and Practice in Qualitative Research’, in. Emerald Group Publishing Limited, pp. 115–133. doi: 10.1108/S2056-375220160000002006.

Halford, G. S. (1982) *The development of thought*. Lawrence Erlbaum Associates.

Halford, G. S. *et al.* (2012) ‘Relational processing is fundamental to the central executive and is limited to four variables’, in *The Cognitive Neuroscience of Working Memory*. doi: 10.1093/acprof:oso/9780198570394.003.0016.

Halford, G. S., Wilson, W. H. and Phillips, S. (2010) ‘Relational knowledge: The foundation of higher cognition’, *Trends in Cognitive Sciences*, pp. 497–505. doi: 10.1016/j.tics.2010.08.005.

Hansen, N. B. and Halskov, K. (2014) ‘Material Interactions with Tangible Tabletops : a Pragmatist Perspective’, *Proceedings of the 8th Nordic Conference on Human-Computer Interaction Fun, Fast, Foundational - NordiCHI ’14*, pp. 441–450. doi: 10.1145/2639189.2639200.

Hansen, T. E. *et al.* (2009) ‘PyMT - A Post-WIMP Multi-Touch User Interface Toolkit’, *Proceedings of the International Conference on Interactive Tabletops and Surfaces (ITS’09)*. New York, New York, USA: ACM Press, pp. 17–24. doi: 10.1145/1731903.1731907.

Harper, R. (2010) *Practical foundations for programming languages*, *Practical Foundations for Programming Languages*. doi: 10.1017/CBO9781139342131.

Hartness, K. T. N. (2009) ‘Game-Related Examples of Artificial Intelligence’, in *FLAIRS Conference*, pp. 172–173.

Hasan, B. (2006) ‘Delineating the effects of general and system-specific computer self-efficacy beliefs on IS acceptance’, *Information and Management*. North-Holland, 43(5), pp. 565–571. doi: 10.1016/j.im.2005.11.005.

Hay, D. B. (2007) ‘Using concept maps to measure deep, surface and non-learning outcomes’, *Studies in Higher Education*, 32(1), pp. 39–57. doi: 10.1080/03075070601099432.

Hay, D., Kinchin, I. and Lygo-Baker, S. (2008) ‘Making learning visible: The role of concept mapping in higher education’, *Studies in Higher Education*, 33(3), pp. 295–311. doi: 10.1080/03075070802049251.

Hayes, J. C. and Kraemer, D. J. M. (2017) ‘Grounded understanding of abstract concepts: The case of STEM learning’, *Cognitive Research: Principles and Implications*. Nature Publishing Group, 2(1), p. 7. doi: 10.1186/s41235-016-0046-z.

Hedrick, T. E. (Terry E., Bickman, L. and Rog, D. J. (1993) *Applied research design : a practical guide*. Sage Publications.

Hejlesen, A. K. and Ovesen, N. (2012) ‘Tangible 3D Modelling: Bridging the Gap Between Physicality and Virtuality’, in Lyndon Buck, Geert Frateur, William Ion, Chris McMahon, Chris Baelus, Guido De Grande, S. V. (ed.) *Design Education for Future Wellbeing : Proceedings of the 14th International Conference on Engineering and Product Design Education*. Glasgow, UK: Design Society, pp. 642–647.

Hengeveld, B. *et al.* (2008) ‘Let me actuate you’, *Proceedings of the 2nd international conference on Tangible and embedded interaction - TEI ’08*, p. 159. doi: 10.1145/1347390.1347426.

Hengeveld, B. *et al.* (2009) ‘Tangibles for toddlers learning language’, *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction - TEI ’09*, p. 161. doi: 10.1145/1517664.1517702.

Hernandez-Barrera, A. (2014) ‘Teaching introduction to robotics: Using a blend of problem- and project-based learning approaches’, in *Conference Proceedings - IEEE SOUTHEASTCON*. doi: 10.1109/SECON.2014.6950686.

Hernández-López, L. *et al.* (2016) ‘Students’ perceptions of the lecturer’s role in management education: Knowledge acquisition and competence development’, *The International Journal of Management Education*, 14(3), pp. 411–421. doi:

10.1016/j.ijme.2016.10.001.

Hidayanto, A. N. *et al.* (2014) ‘Factors Influencing The Use of E-Class’, *Journal of Industrial and Intelligent Information*, 2(2), pp. 121–125. doi: 10.12720/jiii.2.2.121-125.

Hinckley, K. *et al.* (1994) ‘Passive Real-world Interface Props for Neurosurgical Visualization’, *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’94)*, 30, pp. 452–458. doi: 10.1145/191666.191821.

Hinckley, K. *et al.* (1997) ‘The props-based interface for neurosurgical visualization’, *Studies in Health Technology and Informatics*, 39, pp. 552–562. doi: 10.3233/978-1-60750-883-0-552.

Hingston, P., Combes, B. and Masek, M. (2006) ‘Teaching an undergraduate AI course with games and simulation’, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, pp. 494–506. doi: 10.1007/11736639_61.

Hnatyshin, V. Y. and Lobo, A. F. (2008) ‘Undergraduate data communications and networking projects using opnet and wireshark software’, *ACM SIGCSE Bulletin*, 40(1), p. 241. doi: 10.1145/1352322.1352222.

Holden, H. and Rada, R. (2011) ‘Understanding the influence of perceived usability and technology self-efficacy on teachers’ technology acceptance’, *Journal of Research on Technology in Education*, 43(4), pp. 343–367. doi: 10.1080/15391523.2011.10782576.

Holden, R. J. *et al.* (2016) ‘Nurses’ perceptions, acceptance, and use of a novel in-room pediatric ICU technology: testing an expanded technology acceptance model’, *BMC Medical Informatics and Decision Making*, 16(1), pp. 1–10. doi: 10.1186/s12911-016-0388-y.

Holden, R. J. and Karsh, B.-T. (2010) ‘The Technology Acceptance Model: Its past and its future in health care’, *Journal of Biomedical Informatics*, 43(1), pp. 159–172. doi: 10.1016/j.jbi.2009.07.002.

Holland, S. *et al.* (2011) *Whole Body Interaction in Abstract Domains*, *Whole Body Interaction: Human–Computer Interaction Series*. doi: 10.1007/978-0-85729-433-3.

Holmquist, L. E., Redström, J. and Ljungstrand, P. (1999) ‘Token-Based Access to Digital Information’, in *HUC ’99 Proceedings of the 1st international symposium on Handheld and Ubiquitous Computing*, pp. 234–245. doi: 10.1007/3-540-48157-5_22.

Hong, S. J. and Tam, K. Y. (2006) ‘Understanding the adoption of multipurpose information appliances: The case of mobile data services’, *Information Systems Research*, 17(2), pp. 162–179. doi: 10.1016/j.jhazmat.2005.10.004.

Horn, M. S. *et al.* (2007) ‘Putting Tangible User Interfaces in Context : A Unifying Framework for Next Generation HCI’, *Direct*, pp. 1–4.

Horn, M. S. *et al.* (2009) ‘Comparing the use of tangible and graphical programming languages for informal science education’, *Proceedings of the 27th international conference on Human factors in computing systems CHI 09*, 32, p. 975. doi: 10.1145/1518701.1518851.

Horn, M. S., Crouser, R. J. and Bers, M. U. (2012) ‘Tangible interaction and learning: The case for a hybrid approach’, *Personal and Ubiquitous Computing*, 16(4), pp. 379–389. doi: 10.1007/s00779-011-0404-2.

Horn, M. S. and Jacob, R. J. K. (2007) ‘Designing tangible programming languages for classroom use’, in *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI ’07*, p. 159. doi: 10.1145/1226969.1227003.

Horn, M. S., Solovey, E. T. and Jacob, R. J. K. (2008) ‘Tangible Programming and Informal Science Learning: Making TUIs Work for Museums’, *IDC ’08 Proceedings of the 7th international conference on Interaction design and children*. New York, New York, USA: ACM Press, pp. 194–201. doi: 10.1145/1463689.1463756.

Hornecker, E. (2012) ‘Beyond Affordance: Tangibles ’ Hybrid Nature’, in *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, pp. 175–182. doi: 10.1145/2148131.2148168.

Hornecker, E. and Buur, J. (2006) ‘Getting a grip on tangible interaction: a framework on physical space and social interaction’, *Proceedings of the SIGCHI conference on Human Factors in computing systems*, pp. 437–446. doi: http://doi.acm.org/10.1145/1124772.1124838.

Hourcade, J. P. *et al.* (2002) 'KidPad: Collaborative Storytelling for Children', in *CHI'02 extended abstracts on Human factors in computing systems*, pp. 500–501. doi: 10.1145/506443.506449.

Howell, D. C. (1992) *Statistical Methods for Psychology*. Wadsworth Cengage Learning.

Hsia, J. W., Chang, C. C. and Tseng, A. H. (2014) 'Effects of individuals' locus of control and computer self-efficacy on their e-learning acceptance in high-tech companies', *Behaviour and Information Technology*, 33(1), pp. 51–64. doi: 10.1080/0144929X.2012.702284.

Hsiao, C. H. and Yang, C. (2011) 'The intellectual development of the technology acceptance model: A co-citation analysis', *International Journal of Information Management*, 31(2), pp. 128–136. doi: 10.1016/j.ijinfomgt.2010.07.003.

Hu, F. *et al.* (2015) 'Strawbies: Explorations in Tangible Programming', *Proceedings of the 14th International Conference on Interaction Design and Children - IDC '15*, pp. 410–413. doi: 10.1145/2771839.2771866.

Hu, P. J.-H. H., Clark, T. H. K. K. and Ma, W. W. (2003) 'Examining technology acceptance by school teachers: A longitudinal study', *Information and Management*. North-Holland, 41(2), pp. 227–241. doi: 10.1016/S0378-7206(03)00050-8.

Hu, P. J. *et al.* (1999) 'Examining the Technology Acceptance Model Using Physician Acceptance of Telemedicine Technology', *Journal of Management Information Systems*, 16(2), pp. 91–112. doi: 10.1080/07421222.1999.11518247.

Hu, P. J. H., Lin, C. and Chen, H. (2005) 'User acceptance of intelligence and security informatics technology: A study of COPLINK', *Journal of the American Society for Information Science and Technology*, 56(3), pp. 235–244. doi: 10.1002/asi.20124.

Huang, C., Do, E. Y. and Gross, D. (2003) 'MouseHaus Table: a Physical Interface for Urban Design', in *16th Annual ACM Symposium on User Interface Software and Technology*, pp. 41–42.

Huang, H. M., Liaw, S. S. and Lai, C. M. (2016) 'Exploring learner acceptance of the use of virtual reality in medical education: a case study of desktop and projection-based display systems', *Interactive Learning Environments*, 24(1), pp. 3–19. doi: 10.1080/10494820.2013.817436.

Huang, J.-H., Lin, Y.-R. and Chuang, S.-T. (2007) 'Elucidating user behavior of mobile learning. A perspective of the extended technology acceptance model', *The Electronic Library*, 25(5), pp. 585–598. doi: 10.1108/02640470710829569.

Hubwieser, P. *et al.* (2014) 'Perspectives and Visions of Computer Science Education in Primary and Secondary (K-12) Schools', *ACM Transactions on Computing Education*. ACM, 14(2), pp. 1–9. doi: 10.1145/2602482.

Hutchins, E. and Palen, L. (1997) 'Constructing meaning from space, gesture, and speech', *Discourse, tools, and reasoning: Situated cognition and technologically supported environments*, 160, pp. 23–40. doi: 10.1007/978-3-662-03362-3_2.

Iacolina, S. A., Soro, A. and Scateni, R. (2011) 'Improving FTIR based multi-touch sensors with IR shadow tracking', in *Proceedings of the 3rd ACM SIGCHI symposium on Engineering interactive computing systems*. New York, New York, USA: ACM Press, pp. 241–246. doi: http://doi.acm.org/10.1145/1996461.1996529.

Ibrahim, R. *et al.* (2018) 'E-learning acceptance based on technology acceptance model (TAM)', *Journal of Fundamental and Applied Sciences*, 9(4S), p. 871. doi: 10.4314/jfas.v9i4S.50.

Idris, B., Mat Sin, N. and Ya, L. (2015) 'Technology Acceptance Model and the Use Digital Game- Based Learning (DGBL)', *International Journal of Emerging Technology and Advanced Engineerinfg*, 5(6), pp. 5–12. doi: 10.24178/irjece.2015.1.1.24.

Igbaria, M. and Parasuraman, S. (1989) 'A Path Analytic Study of Individual Characteristics, Computer Anxiety and Attitudes toward Microcomputers', *Journal of Management*, 15(3), pp. 373–388. doi: 10.1177/014920638901500302.

Ishibushi, S. *et al.* (2015) 'Statistical localization exploiting convolutional neural network for an autonomous vehicle', in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, pp. 1369–1375. doi: 10.1109/IECON.2015.7392291.

Ishii, H. (1998) ‘Tangible Bits: Beyond Graphical User Interface’, in *APCHI ’98 Proceedings of the Third Asian Pacific Computer and Human Interaction*. IEEE Computer Society Washington, DC, US, p. xvii.

Ishii, H. *et al.* (2004) ‘Bringing Clay and Sand into Digital Design — Continuous Tangible user Interfaces’, *BT Technology Journal*, 22(4), pp. 287–299. doi: 10.1023/B:BTTJ.0000047607.16164.16.

Ishii, H. (2006) ‘Tangible User Interfaces’, *CHI 2006 workshop*. 1st edn. Edited by Sears A and J. Jacko. Montreal, Canada: ACM, pp. 1–17.

Ishii, H. (2008a) ‘Tangible bits: beyond pixels’, *Proceedings of the 2nd international conference on Tangible and Embedded Intreaction (TEI ’08)*, pp. xv–xxv. doi: 10.1145/1347390.1347392.

Ishii, H. (2008b) ‘The tangible user interface and its evolution’, *Communications of the ACM*, 51(6), pp. 32–36. doi: 10.1145/1349026.1349034.

Ishii, H. (2009) ‘Tangible User Interfaces’, in Sears A and Jacko, J. (eds) *Human-Computer Interaction: Design Issues, Solutions, and Applications*. 1st edn. Montreal, Canada, pp. 1–17.

Ishii, H. *et al.* (2012) ‘Radical atoms: beyond tangible bits, toward transformable materials’, *interactions*. ACM, 19(1), p. 38. doi: 10.1145/2065327.2065337.

Ishii, H., Mazalek, A. and Lee, J. (2001) ‘Bottles as a minimal interface to access digital information’, *CHI ’01 extended abstracts on Human factors in computing systems*, pp. 187–188. doi: 10.1145/634067.634180.

Ishii, H. and Ullmer, B. (1997) ‘Tangible bits: towards seamless interfaces between people, bits, and atoms’, in *Proceedings of the 8th international conference on Intelligent user interfaces*, pp. 3–3. doi: http://doi.acm.org/10.1145/604045.604048.

Itoh, Y. *et al.* (2004) ‘TSU.MI.KI: Stimulating children’s creativity and imagination with interactive blocks’, in *Proceedings - Second International Conference on Creating, Connecting and Collaborating Through Computing*, pp. 62–70. doi: 10.1109/C5.2004.1314370.

Jacob, R. J. K. *et al.* (2002) ‘A tangible interface for organizing information using a grid', *Proceedings of the SIGCHI*, (1), p. 339. doi: 10.1145/503376.503437.

Janitor, J., Jakab, F. and Kniewald, K. (2010) 'Visual learning tools for teaching/learning computer networks: Cisco Networking Academy and packet tracer', in *6th International Conference on Networking and Services, ICNS 2010, Includes LMPCNA 2010; INTENSIVE 2010*, pp. 351–355. doi: 10.1109/ICNS.2010.55.

Janota, A., ŠimÁk, V. and Hrbček, J. (2014) 'Learning Search Algorithms: An Educational View', *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 8(4), pp. 565–570. doi: 10.12716/1001.08.04.11.

JapaneseIQTest (2015) *Japanese IQ Test - Free Intelligence Test Game Online*. Available at: http://www.japaneseiqtest.net/ (Accessed: 8 October 2017).

Jarušek, P. and Pelánek, R. (2012) 'Analysis of a Simple Model of Problem Solving Times', in *International Conference on Intelligent Tutoring Systems*. Springer, Berlin, Heidelberg, pp. 379–388. doi: 10.1007/978-3-642-30950-2_49.

Jarvis, P. (1992) *Paradoxes of Learning. On Becoming an Individual in Society*. Routledge.

Jarvis, P. (2014) 'From adult education to lifelong learning and beyond', *Comparative Education*, 50(1), pp. 45–57. doi: 10.1080/03050068.2013.871832.

Jasperson, J., Carter, P. E. and Zmud, R. W. (2005) 'A Comprehensive Conceptualization of Post-Adoptive Behaviors Associated With Information Technology Enabled Work Systems', *Management Information Systems Quarterly*, 29(3), pp. 525–557. doi: 10.2307/25148694.

Jesin, A. . (2014) *Packet Tracer Network Simulator.*, *Packt Publishing Ltd*. doi: 9781782170433.

Jia, Y. *et al.* (2014) 'Caffe: Convolutional Architecture for Fast Feature Embedding', in *Proceedings of the ACM International Conference on Multimedia - MM '14*. New York, New York, USA: ACM Press, pp. 675–678. doi: 10.1145/2647868.2654889.

Jingfeng, X. (2011) 'An anthropological emic-etic perspective on open access practices', *Journal of Documentation*. doi: 10.1108/00220411111105461.

Johnson, M. (1987) *The body in the mind : the bodily basis of meaning, imagination, and reason*. University of Chicago Press.

Jones, G. and Sallis, E. (2013) *Knowledge management in education: Enhancing learning & education*, *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki*. Kogan Page.

De Jong, T. and Van Joolingen, W. R. (1998) 'Scientific Discovery Learning with Computer Simulations of Conceptual Domains', *Review of Educational Research*, 68(2), pp. 179–201. doi: 10.3102/00346543068002179.

Joo, Y. J., So, H. J. and Kim, N. H. (2018) 'Examination of relationships among students' self-determination, technology acceptance, satisfaction, and continuance intention to use K-MOOCs', *Computers and Education*. Pergamon, 122, pp. 260–272. doi: 10.1016/j.compedu.2018.01.003.

Jordà, S. *et al.* (2007) 'The reacTable : Exploring the Synergy between Live Music Performance and Tabletop Tangible Interfaces', in *Proceedings of Conference on Tangible and Embedded Interaction TEI '07*, pp. 139–146. doi: 10.1145/1226969.1226998.

Kalelioğlu, F. (2015) 'A new way of teaching programming skills to K-12 students: Code.org', *Computers in Human Behavior*. Pergamon, 52, pp. 200–210. doi: 10.1016/J.CHB.2015.05.047.

Kaltenbrunner, M. *et al.* (2005) 'TUIO: A protocol for table-top tangible user interfaces', *Neuroinformatics*, pp. 1–5.

Kaltenbrunner, M. (2009) 'reacTIVision and TUIO : A Tangible Tabletop Toolkit', *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, pp. 9–16. doi: 10.1145/1731903.1731906.

Kaltenbrunner, M. and Bencina, R. (2007a) 'reacTIVision: a computer-vision framework for table-based tangible interaction', *Proceedings of the 1st international conference on Tangible and embedded interaction*, pp. 69–74. doi: 10.1145/1226969.1226983.

Kaltenbrunner, M. and Bencina, R. (2007b) 'reacTIVision', *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07*, (JANUARY

2007), p. 69. doi: 10.1145/1226969.1226983.

Kaltenbrunner, M. and Bencina, R. (2016) *reacTIVision: a toolkit for tangible multi-touch surfaces*. Available at: http://reactivision.sourceforge.net/ (Accessed: 20 January 2017).

Karahanna, E., Agarwal, R. & Angst, C. M. (2006) 'Reconceptualizing Compatability Beliefs in Technology Acceptance Research', *MIS Ouarterly*, 30(4), pp. 781–804. doi: 10.2307/25148754.

Karahanna, E., Straub, D. W. and Chervany, N. L. (1999) 'Information Technology Adoption Across Time: A Cross-Sectional Comparison of Pre-Adoption and Post-Adoption Beliefs', *MIS Quarterly*. Management Information Systems Research Center, University of Minnesota, 23(2), p. 183. doi: 10.2307/249751.

Karanya Sitdhisanguan *et al.* (2007) 'Comparative study of WIMP and tangible user interfaces in training shape matching skill for autistic children', in *TENCON 2007 - 2007 IEEE Region 10 Conference*. IEEE, pp. 1–4. doi: 10.1109/TENCON.2007.4428939.

Kato, H. and Billinghurst, M. (1999) 'Marker tracking and HMD calibration for a video-based augmented reality conferencing system', in *Proceedings 2nd IEEE and ACM International Workshop on Augmented Reality (IWAR'99)*. IEEE Comput. Soc, pp. 85–94. doi: 10.1109/IWAR.1999.803809.

Kawulich, B. B. (2005) 'Participant observation as a data collection method', *Forum Qualitative Sozialforschung*.

Kazu, İ. Y. (2009) 'The Effect of Learning Styles on Education and the Teaching Process', *Journal of Social Sciences*, 5(2), pp. 85–94. doi: 10.1078/1439-1791-00218.

Keller, J. (1983) 'Motivational design of instruction', *Instructional -design theories and models*, pp. 386–434.

Keller, J. M. (1999) 'Using the arcs motivational process in computer-based instruction and distance education', *New Directions for Teaching and Learning*, 1999(78), pp. 37–47. doi: 10.1002/tl.7804.

Keller, J. M. (2010) 'What is Motivational Design?', in *Motivational Design for Learning* *and Performance*, pp. 21–41. doi: 10.1007/978-1-4419-1250-3_2.

Kenneth, S. and Babinec, A. (2017) 'Data Analysis with IBM SPSS Statistics: Implementing data modeling, descriptive statistics and ANOVA'. Packt Publishing, p. 446.

Kharb, P. *et al.* (2013) 'The learning styles and the preferred teaching-learning strategies of first year medical students', *Journal of Clinical and Diagnostic Research*, 7(6), pp. 1089–1092. doi: 10.7860/JCDR/2013/5809.3090.

Kikin-Gil, E. (2006) 'The Light-Wall: Tangible user interfaces for learning systems thinking', *Personal and Ubiquitous Computing*, 10(2–3), pp. 181–182. doi: 10.1007/s00779-005-0014-y.

Kim, L. *et al.* (2007) 'A tangible user interface with multimodal feedback', in *Proceedings of the 12th international conference on Human-computer interaction*. doi: 10.1007/978-3-540-73110-8.

Kim, M. J. and Maher, M. Lou (2008) 'The Impact of Tangible User Interfaces on Designers' Spatial Cognition', *Human–Computer Interaction*. Taylor & Francis Group , 23(2), pp. 101–137. doi: 10.1080/07370020802016415.

King, J. and Just, M. A. (1991) 'Individual differences in syntactic processing: The role of working memory', *Journal of Memory and Language*, 30(5), pp. 580–602. doi: 10.1016/0749-596X(91)90027-H.

King, P. J. (2011) *dlpjava: a data link protocol simulator*. Available at: https://www.macs.hw.ac.uk/~pjbk/dlpjava/ (Accessed: 23 February 2018).

King, W. R. and He, J. (2006) 'A meta-analysis of the technology acceptance model', *Information and Management*, 43(6), pp. 740–755. doi: 10.1016/j.im.2006.05.003.

Kirakowski, J. and Corbett, M. (1993) 'SUMI: the Software Usability Measurement Inventory', *British Journal of Educational Technology*, 24(3), pp. 210–212. doi: 10.1111/j.1467-8535.1993.tb00076.x.

Kirby, B. T., Ashley-Rollman, M. and Goldstein, S. C. (2011) 'Blinky blocks: a physical ensemble programming platform', in *Proceedings of the 2011 annual conference extended abstracts on Human factors in computing systems - CHI EA '11*, pp. 1111–

1116. doi: 10.1145/1979742.1979712.

Kirschner, P. A. (2002) ‘Cognitive load theory: Implications of cognitive load theory on the design of learning’, *Learning and Instruction*, pp. 1–10. doi: 10.1016/S0959-4752(01)00014-7.

Kitamura, Y., Itoh, Y. and Kishino, F. (2001) ‘Real-time 3D interaction with ActiveCube’, *CHI ’01 extended abstracts on Human factors in computer systems - CHI ’01*, p. 2. doi: 10.1145/634274.634277.

Klahr, D., Triona, L. M. and Williams, C. (2007) ‘Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children’, *Journal of Research in Science Teaching*. Wiley-Blackwell, 44(1), pp. 183–203. doi: 10.1002/tea.20152.

Klemmer, S. *et al.* (2004) ‘Papier-Mâché: Toolkit Support for Tangible Input’, *proc. ACM CHI 2004, Vienna, Austria, April 24*, 6(1), pp. 399–406. doi: 10.1145/985692.985743.

Klemmer, S. R., Hartmann, B. and Takayama, L. (2006) ‘How Bodies Matter: Five Themes for Interaction Design’, in *DIS ‘06 Proceedings of the 6th conference on Designing Interactive Systems*, pp. 140–149. doi: 10.1145/1142405.1142429.

Kline, R. B. (2011) *Principles and practice of structural equation modeling*, *Structural Equation Modeling*. doi: 10.1038/156278a0.

Klokmose, C. N. *et al.* (2014) ‘Bullseye: High-precision fiducial tracking for table-based tangible interaction’, *Its*, pp. 269–278. doi: 10.1145/2669485.2669503.

Knowles, M. E. and Delaney, P. F. (2005) ‘Lasting reductions in illegal moves following an increase in their cost: evidence from river-crossing problems.’, *Journal of experimental psychology. Learning, memory, and cognition*, 31(4), pp. 670–82. doi: 10.1037/0278-7393.31.4.670.

Kobayashi, K. *et al.* (2003a) ‘A tangible interface for IP network simulation’, in *CHI ’03 extended abstracts on Human factors in computing systems - CHI ’03*, pp. 800–801. doi: 10.1145/765891.766000.

Kobayashi, K. *et al.* (2003b) ‘IP network designer: Interface for IP network simulation’, in *Proceedings - 2nd IEEE and ACM International Symposium on Mixed and Augmented Reality, ISMAR 2003*, pp. 327–328. doi: 10.1109/ISMAR.2003.1240743.

Kobayashi, K. *et al.* (2006) ‘Collaborative simulation interface for planning disaster measures’, *CHI ’06 extended abstracts on Human factors in computing systems - CHI EA ’06*, p. 977. doi: 10.1145/1125451.1125639.

Koehler, M. J. *et al.* (2014) ‘The Technological Pedagogical Content Knowledge Framework’, in *Handbook of Research on Educational Communications and Technology*. New York, NY: Springer New York, pp. 101–111. doi: 10.1007/978-1-4614-3185-5_9.

Kolb, D. a. (1984) ‘Experiential learning: experience as the source of learning and development’, *Journal of Organizational Behavior*, pp. 19–38. doi: 10.1002/job.4030080408.

Kolb, D. A., Boyatzis, R. E. and Mainemelis, C. (2000) ‘Experiential Learning Theory: Previous Research and New Directions’, *Perspectives on thinking learning and cognitive styles*, 1(216), pp. 227–247. doi: 10.5465/AMLE.2005.17268566.

Koleva, B. *et al.* (2003) ‘A Framework for Tangible User Interfaces’, in *Physical Interaction (PI03) Workshop on Real World User Interfaces*, pp. 46–50. doi: 10.1007/s00779-005-0050-7.

Kölling, M. (1989) ‘The problem of teaching object-oriented programming’, *Journal of Object-oriented programming*, 11(8), pp. 8--15.

Konrad, M. (2012) *Building a Portable Low Cost Tangible User Interface Based on a Tablet Computer*. Available at: https://mkonrad.net/projects/ipad2tui.html (Accessed: 23 February 2017).

Kotovsky, K. and Simon, H. A. (1990) ‘What makes some problems really hard: Explorations in the problem space of difficulty’, *Cognitive Psychology*. Academic Press, 22(2), pp. 143–183. doi: 10.1016/0010-0285(90)90014-U.

Koufaris, M. (2002) ‘Applying the Technology Acceptance Model and flow theory to online Consumer Behavior’, *Information Systems Research*, 13(2), pp. 205–223. doi: 10.1287/isre.13.2.205.83.

Krasner, G. E. and Pope, S. T. (1988) 'A Description of the Model-View-Controller User Interface Paradigm in the Smalltalk-80 System', *Journal of object oriented programming*, 1(3), pp. 26–49. doi: 10.1.1.47.366.

Kreijns, K., Kirschner, P. A. and Jochems, W. (2003) 'Identifying the pitfalls for social interaction in computer-supported collaborative learning environments: a review of the research', *Computers in Human Behavior*. Pergamon, 19(3), pp. 335–353. doi: 10.1016/S0747-5632(02)00057-2.

Kres, H. (1983) 'The Multivariate Normal Distribution with Equal Correlations: Tables of S. S. Gupta', in Kres, H. (ed.) *Statistical Tables for Multivariate Analysis*, pp. 184–203. doi: 10.1007/978-1-4612-5609-0_10.

Krug, S. (2006) *Don't Make Me Think: A Common Sense Approach to Web Usability*, *Don't Make Me Think! A Common Sense Aproach to Web Usability*. doi: 10.1098/rspb.2009.1614.

Kubicki, S. *et al.* (2015) 'RFID interactive tabletop application with tangible objects: exploratory study to observe young children' behaviors', *Personal and Ubiquitous Computing*, 19(8), pp. 1259–1274. doi: 10.1007/s00779-015-0891-7.

Kubicki, S., Lepreux, S. and Kolski, C. (2012) 'RFID-driven situation awareness on TangiSense, a table interacting with tangible objects', *Personal and Ubiquitous Computing*, 16(8), pp. 1079–1094. doi: 10.1007/s00779-011-0442-9.

Kuc, R., Jackson, E. W. and Kuc, A. (2004) 'Teaching Introductory Autonomous Robotics With JavaScript Simulations and Actual Robots', *IEEE Transactions on Education*, 47(1), pp. 74–82.

Kumar, D. and Meeden, L. (1998) 'A robot laboratory for teaching artificial intelligence', *ACM SIGCSE Bulletin*, 30(1), pp. 341–344. doi: 10.1145/274790.274326.

Kuzuoka, H. *et al.* (2014) 'Tangible Earth: Tangible Learning Environment for Astronomy Education', in *Proceedings of the second international conference on Human-agent interaction - HAI '14*. New York, New York, USA: ACM Press, pp. 23–27. doi: 10.1145/2658861.2658870.

Lacage, M. and Henderson, T. R. (2006) 'Yet another network simulator', *Proceeding* *from the 2006 workshop on ns-2: the IP network simulator - WNS2 '06*, p. 12. doi: 10.1145/1190455.1190467.

Lackner, T. M. *et al.* (1999) 'Sensory puzzles', in *CHI '99 extended abstracts on Human factors in computing systems - CHI '99*. New York, New York, USA: ACM Press, p. 270. doi: 10.1145/632716.632882.

Lambach, D., Kärger, C. and Goerres, A. (2017) 'Inverting the large lecture class: Active learning in an introductory international relations course', *European Political Science*, 16(4), pp. 553–569. doi: 10.1057/s41304-016-0078-3.

Lan, C. H. (2007) 'Tools for Teaching Computer Networking and Hardware Concepts', *Educational Technology & Society*, 10(1), pp. 268–270. doi: 10.1111/j.1467-8535.2007.00772_18.x.

Larkin, J. H. *et al.* (1980) 'Models of competence in solving physics problems', *Cognitive Science*, 4(4), pp. 317–345. doi: 10.1016/S0364-0213(80)80008-5.

Laru, J. and Järvelä, S. (2013) 'Using gartner's Hype Cycle as a basis to analyze research on the educational use of ubiquitous computing', in *Computer-Supported Collaborative Learning Conference, CSCL*, pp. 280–287.

Laurillard, D. (2013) *Rethinking university teaching: A conversational framework for the effective use of learning technologies.*, *Rethinking university teaching A conversational framework for the effective use of learning technologies*. doi: 10.4324/9780203304846.

Lee, C. and Coughlin, J. F. (2015) 'Perspective: Older Adults' Adoption of Technology: An Integrated Approach to Identifying Determinants and Barriers', *Journal of Product Innovation Management*. Wiley/Blackwell (10.1111), 32(5), pp. 747–759. doi: 10.1111/jpim.12176.

Lee, M. K. O., Cheung, C. M. K. and Chen, Z. (2005) 'Acceptance of Internet-based learning medium: The role of extrinsic and intrinsic motivation', *Information and Management*, pp. 1095–1104. doi: 10.1016/j.im.2003.10.007.

Lee, S. and Kim, B. G. (2009) 'Factors affecting the usage of intranet: A confirmatory study', *Computers in Human Behavior*, 25(1), pp. 191–201. doi:

10.1016/j.chb.2008.08.007.

Lee, W., Xiong, L. and Hu, C. (2012) ‘The effect of Facebook users’ arousal and valence on intention to go to the festival: Applying an extension of the technology acceptance model’, *International Journal of Hospitality Management*, 31(3), pp. 819–827. doi: 10.1016/j.ijhm.2011.09.018.

Lee, Y. H., Hsiao, C. and Purnomo, S. H. (2014) ‘An empirical examination of individual and system characteristics on enhancing e-learning acceptance’, *Australasian Journal of Educational Technology*, 30(5), pp. 562–579. doi: 10.14742/ajet.381.

Lee, Y., Kozar, K. A. and Larsen, K. R. T. (2003) ‘The Technology Acceptance Model: Past, Present, and Future’, *Communications of the Association for Information Systems*, 12(50), pp. 752–780. doi: 10.1037/0011816.

Legris, P., Ingham, J. and Collerette, P. (2003) ‘Why do people use information technology? A critical review of the technology acceptance model’, *Information & Management*, 40(3), pp. 191–204. doi: Doi: 10.1016/s0378-7206(01)00143-4.

Lepper, M. R. (1988) ‘Motivational Considerations in the Study of Instruction’, *Cognition and Instruction*, 5(4), pp. 289–309. doi: 10.1207/s1532690xci0504_3.

Lepper, M. R. and Chabay, R. W. (1985) ‘Intrinsic Motivation and Instruction: Conflicting Views on the Role of Motivational Processes in Computer-Based Education’, *Educational Psychologist*, 20(4), pp. 217–230. doi: 10.1207/s15326985ep2004_6.

Leroux, H., Réquilé-Romanczuk, A. and Mingins, C. (2003) ‘JACOT: A Tool to Dynamically Visualise the Execution of Concurrent Java Programs’, in *Proceedings of the 2nd international conference on Principles and practice of programming in Java*, pp. 201–206.

Levitin, A. and Papalaskari, M.-A. (2002) ‘Using puzzles in teaching algorithms’, *ACM SIGCSE Bulletin*, 34, pp. 292–296. doi: 10.1145/563517.563456.

Lewis, P. M., Bernstein, A. and Kifer, M. (2002) ‘Databases and transaction processing’, *ACM SIGMOD Record*. ACM, 31(1), p. 74. doi: 10.1145/507338.507354.

Li, X., Yong, G. and Wu, M. (2009) ‘Web-based virtual laboratory platform for computer network', in *Proceedings - 2009 International Conference on Computational Intelligence and Software Engineering, CiSE 2009*. doi: 10.1109/CISE.2009.5365506.

Liaw, S. S. and Huang, H. M. (2003) 'An investigation of user attitudes toward search engines as an information retrieval tool', *Computers in Human Behavior*, 19(6), pp. 751–765. doi: 10.1016/S0747-5632(03)00009-8.

Liberatore, M. J. and Nydick, R. L. (1999) 'The Teachers' Forum: Breaking the Mold—A New Approach to Teaching the First MBA Course in Management Science', *INTERFACES*, 29(4), pp. 99–116.

Lin, S. C., Persada, S. F. and Nadlifatin, R. (2014) 'A study of student behavior in accepting the Blackboard Learning System: A Technology Acceptance Model (TAM) approach', in *Proceedings of the 2014 IEEE 18th International Conference on Computer Supported Cooperative Work in Design, CSCWD 2014*, pp. 457–462. doi: 10.1109/CSCWD.2014.6846888.

Linge, N. and Parsons, D. (2006) 'Problem-based learning as an effective tool for teaching computer network design', *IEEE Transactions on Education*, 49(1), pp. 5–10. doi: 10.1109/TE.2005.852600.

Lokare, V. T., Jadhav, P. M. and Patil, S. S. (2018) 'An Integrated Approach for Teaching Object Oriented Programming (C++) Course', *Journal of Engineering Education Transformations*, 31(3), pp. 17–23. doi: 10.16920/JEET/2018/V31I3/120744.

Louw, J., Swart, A. J. and Bere, A. (2016) 'Extending the Technology Acceptance Model for E- learning Discussion Forum Adoption', in *6th Africian Engineering Education Association Conference (AEEA2016)*. South Africa, pp. 87–92.

Lowry, P. B. and Gaskin, J. (2014) 'Partial least squares (PLS) structural equation modeling (SEM) for building and testing behavioral causal theory: When to choose it and how to use it', *IEEE Transactions on Professional Communication*, 57(2), pp. 123–146. doi: 10.1109/TPC.2014.2312452.

Lu, H.-K., Lin, P.-C. and Chen, A. N. (2017) 'An empirical study of behavioral intention model: Using learning and teaching styles as individual differences', *Journal of*

Discrete Mathematical Sciences and Cryptography. Taylor & Francis, 20(1), pp. 19–41. doi: 10.1080/09720529.2016.1177968.

Lu, J. *et al.* (2003) 'Technology acceptance model for wireless Internet', *Internet Research: Electronic Networking Applications and Policy*, 13(3), pp. 206–222. doi: 10.1108/10662240310478222.

Lucignano, L. *et al.* (2014) 'My hands or my mouse: Comparing a tangible and graphical user interface using eye-tracking data.', in *Fablearn 2014 (No. EPFL-CONF-204226).*

Luderschmidt, J. (2011) *The Multi-Touch Table Virttable*. Available at: http://johannesluderschmidt.de/lang/en-us/the-multi-touch-table-virttable/153/ (Accessed: 23 February 2017).

Luderschmidt, J. and Bauer, I. (2010) 'TUIO AS3: A Multi-Touch and Tangible User Interface Rapid Prototyping Toolkit for Tabletop Interaction', *ITG/GI Workshop on Self-Integrating Systems for Better Living Environments - Sensyble Workshop*, pp. 1–8.

Lund, A. M. (2001) 'Measuring usability with the USE questionnaire', *Usability interface*, 8(2), pp. 3–6. doi: 10.1177/1078087402250360.

Luttrell, W. (2010) *Qualitative educational research : readings in reflexive methodology and transformative practice*. Routledge.

Ma, Q. and Liu, L. (2004) 'The technology acceptance model: A meta-analysis of empirical findings', *Journal of Organizational and End User Computing*, 16(1), pp. 59–72. doi: 10.1016/j.im.2006.05.003.

Macharia, J. and Nyakwende, E. (2010) 'The influence of E-mail on students' learning in higher education: An extension to the Technology Acceptance Model (TAM)', *Asian Journal of Information Technology*, 9(3), pp. 123–132. doi: 10.3923/ajit.2010.123.132.

Macintyre, B. *et al.* (2003) 'DART: The designer's augmented reality toolkit', in *Proceedings - 2nd IEEE and ACM International Symposium on Mixed and Augmented Reality, ISMAR 2003*, pp. 329–330. doi: 10.1109/ISMAR.2003.1240744.

Mackay, W. E. and Fayard, A. (1999) 'Designing Interactive Paper: Lessons from three Augmented Reality Projects', in *In Proceedings of IWAR'98, International Workshop* *on Augmented Reality*, pp. 81–90.

Madni, T. M., Sulaiman, S. B. and Tahir, M. (2013) ‘Content-orientation for collaborative learning using tabletop surfaces’, in *2013 International Conference on Information Science and Applications, ICISA 2013*. doi: 10.1109/ICISA.2013.6579376.

Magerkurth, C. and Tandler, P. (2002) ‘Augmenting tabletop design for computer-supported cooperative work’, in *Workshop on Co-located Tabletop Collaboration: Technologies and Directions at CSCW*, p. 2002.

Maher, M. Lou and Kim, M. J. (2006) ‘Studying designers using a tabletop system for 3D design with a focus on the impact on spatial cognition’, *Proceedings of the First IEEE International Workshop on Horizontal Interactive Human-Computer Systems, TABLETOP’06*, 2006, pp. 105–112. doi: 10.1109/TABLETOP.2006.28.

Male, S. A., Guzzomi, A. L. and Baillie, C. A. (2012) ‘Interdisciplinary threshold concepts in engineering’, in *Proceedings of Higher Education Research and Development Society of Australasia Conference, Hobart*.

Male, S. A., Macnish, C. K. and Baillie, C. A. (2012) ‘Engaging Students in Engineering Curriculum Renewal using Threshold Concepts’, in *th International CDIO Conference, Queensland University of Technology,* . Brisbane.

Malizia, A., Turchi, T. and Olsen, K. A. (2017) ‘Block-oriented programming with tangibles: An engaging way to learn computational thinking skills’, in *2017 IEEE Blocks and Beyond Workshop (B&B)*. IEEE, pp. 61–64. doi: 10.1109/BLOCKS.2017.8120413.

Malnati, G., Cuva, C. M. and Barberis, C. (2007) ‘JThreadSpy: Teaching Multithreading Programming by Analyzing Execution Traces’, *Proceedings of the 2007 ACM workshop on Parallel and distributed systems: testing and debugging*, pp. 3–13. doi: 10.1145/1273647.1273650.

Maloney, M. and Lally, B. (1998) ‘The Relationship between Attendance at University Lectures and Examination Performance’, *The Irish Journal of Education / Iris Eireannach an Oideachais*. Educational Research Centre, 29, pp. 52–62. doi: 10.2307/30071605.

Manches, A. and O'Malley, C. (2012) 'Tangibles for learning: A representational analysis of physical manipulation', *Personal and Ubiquitous Computing*, 16(4), pp. 405–419. doi: 10.1007/s00779-011-0406-0.

Mandelbaum, A. and Zeltyn, S. (2010) 'Service Engineering: Data-Based Course Development and Teaching', *INFORMS Transactions on Education*, 11(1), pp. 3–19. doi: 10.1287/ited.1100.0058.

Maquil, V., Psik, T. and Wagner, I. (2008) 'The ColorTable: a design story', *Proceedings ot TEI'08*, pp. 97–104. doi: 10.1145/1347390.1347412.

Maquil, V. and Ras, E. (2012) 'Collaborative problem solving with objects: Physical aspects of a tangible tabletop in technology-based assessment', in *From Research to Practice in the Design of Cooperative Systems: Results and Open Challenges - Proceedings of the 10th International Conference on the Design of Cooperative Systems, COOP 2012*, pp. 153–166. doi: 10.1007/978-1-4471-4093-1_11.

Marangunić, N. and Granić, A. (2015) 'Technology acceptance model: a literature review from 1986 to 2013', *Universal Access in the Information Society*, 14(1), pp. 81–95. doi: 10.1007/s10209-014-0348-1.

Marco, J. *et al.* (2009) 'Bringing Tabletop Technologies to Kindergarten Children', in *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology*, pp. 103–111. doi: 10.1007/s00779-012-0522-5.

Marco, J., Cerezo, E. and Baldassarri, S. (2012) 'ToyVisionn: A Toolkit for Prototyping Tabletop Tangible Games', *Proceedings of the 4th ACM SIGCHI symposium on Engineering interactive computing systems - EICS '12*, p. 71. doi: 10.1145/2305484.2305498.

María, J. *et al.* (2006) 'Guided practical activities for learning programming languages', *Current Developments in Technology-Assisted Education*, pp. 871–875.

Mariappan, M. *et al.* (2017) 'Early Childhood Educational Robotic System (C-Block): A Design Methodology', *Advanced Science Letters*, 23(11), pp. 11206–11210. doi: 10.1166/asl.2017.10252.

Markman, A. B. and Stilwell, C. H. (2001) ‘Role-governed categories’, *Journal of Experimental and Theoretical Artificial Intelligence*, 13(4), pp. 329–358. doi: 10.1080/09528130110100252.

Markova, M. S. (2013) ‘How does the tangible object affect motor skill learning?’, *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction - TEI ’14*. New York, New York, USA: ACM Press, pp. 305–308. doi: 10.1145/2540930.2558150.

Marshall, P. (2007) ‘Do tangible interfaces enhance learning?’, in *Proceedings of the 1st international conference on Tangible and embedded interaction*, pp. 167–170. doi: 10.1145/1226969.1227004.

Marshall, P., Cheng, P. C.-H. and Luckin, R. (2010) ‘Tangibles in the Balance: a Discovery Learning Task with Physical or Graphical Materials’, *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction ACM*, pp. 153–160. doi: 10.1145/1709886.1709914.

Marshall, P., Price, S. and Rogers, Y. (2003) ‘Conceptualising tangibles to support learning’, *IDC ’03: Proceedings of the 2003 conference on Interaction design and children*, (October), pp. 101–109. doi: 10.1145/953536.953551.

Marshall, P., Rogers, Y. and Hornecker, E. (2007) ‘Are tangible interfaces really any better than other kinds of interfaces ?’, *CHI’07 workshop on Tangible User Interfaces in Context & Theory*, (i), p. 28.

Martin, F. G. (1995) ‘A Toolkit for Learning: Technology of the MIT LEGO Robot Design Competition’, *Design*.

Martinez-Maldonado, R. S. B. B. S. J. E. (2017) ‘Learning Analytics for Natural User Interfaces.’, *Journal of Learning Analytics*. Society for Learning Analytics Research. 121 Pointe Marsan, Beaumont, AB T4X 0A2, Canada. Tel: +61-429-920-838; e-mail: info@solaresearch.org; Web site: http://learning-analytics.info/journals/index.php/JLA/, 4(1), pp. 24–57.

Martinez-Maldonado, R., Yacef, K. and Kay, J. (2015) ‘TSCL: A conceptual model to inform understanding of collaborative learning processes at interactive tabletops’, *International Journal of Human Computer Studies*, 83, pp. 62–82. doi: 10.1016/j.ijhcs.2015.05.001.

Martins, C., Oliveira, T. and Popovič, A. (2014) 'Understanding the internet banking adoption: A unified theory of acceptance and use of technology and perceived risk application', *International Journal of Information Management*, 34(1), pp. 1–13. doi: 10.1016/j.ijinfomgt.2013.06.002.

Masrom, M. (2007) 'Technology acceptance model and E-learning', *12th International Conference on Education*, (May), pp. 21–24. doi: 10.1002/dir.

Mathieson, K. (1991) 'Predicting User Intentions: Comparing the Technology Acceptance Model with the Theory of Planned Behavior.', *Information Systems Research*, 2(3), pp. 173–191. doi: Article.

Maybery, M. T., Bain, J. D. and Halford, G. S. (1986) 'Information-processing demands of transitive inference', *Journal of Experimental Psychology: Learning, Memory and Cognition*, 12(4), pp. 600–613. doi: 10.1037//0278-7393.12.4.600.

Mazalek, A., Davenport, G. and Ishii, H. (2002) 'Tangible viewpoints: a physical approach to multimedia stories', *MULTIMEDIA '02: Proceedings of the tenth ACM international conference on Multimedia*, pp. 153–160. doi: http://doi.acm.org/10.1145/641007.641037.

Mazalek, A. and van den Hoven, E. (2009) 'Framing tangible interaction frameworks', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 23(03), p. 225. doi: 10.1017/S0890060409000201.

Mazalek, A. L. I. (2006) 'Tangible toolkits. Integrating application development across diverse multi-user and tangible interaction platforms', *Let's get physical workshop. Design Computing and Cognition 2006*.

Mazalek, A., Wood, A. and Ishii, H. (2001) 'genieBottles: An Interactive Narrative in Bottles', *Annual Conference on Computer Graphics - SIGGRAPH*, p. 2.

Mazer, J. P. and Hess, J. A. (2017) 'What is the place of lecture in higher education?', *Communication Education*, pp. 236–237. doi: 10.1080/03634523.2017.1287411.

McBurney, D. and White, T. L. (2010) *Research methods*. Wadsworth Cengage

Learning.

McCredden, J. E. *et al.* (2016) 'Don't blame the student, it's in their mind: Helping engineering students to grasp complex concepts', in *AAEE2016 CONFERENCE*. Coffs Harbour, Australia, pp. 1–10.

McDonald, C. (2015) *The cnet network simulator (v3.3.3)*. Available at: http://www.csse.uwa.edu.au/cnet/ (Accessed: 23 February 2018).

McGee, D. R. *et al.* (2002) 'Comparing paper and tangible, multimodal tools', *Proceedings of the SIGCHI conference on Human factors in computing systems: Changing our world, changing ourselves*, (1), pp. 407–414. doi: http://doi.acm.org/10.1145/503376.503449.

McGovern, A., Tidwell, Z. and Rushing, D. (2011) 'Teaching Introductory Artificial Intelligence through Java-Based Games', *Proceedings of the Second Symposium on Educational Advances in Artificial Intelligence*, pp. 1729–1736.

McNerney, T. S. (2000) 'Tangible Programming Bricks : An approach to making programming accessible to everyone', *Media*, (June 1983).

McNerney, T. S. (2004) 'From turtles to Tangible Programming Bricks: Explorations in physical language design', *Personal and Ubiquitous Computing*, 8(5), pp. 326–337. doi: 10.1007/s00779-004-0295-6.

McSporran, M. and King, C. (2005) 'Blended is better: choosing educational delivery methods.', *World Conference on Educational Multimedia, Hypermedia and Telecommunications*, pp. 4932–4939.

Mehner, K. (2002) 'JaVis: A UML-Based Visualization and Debugging Environment for Concurrent Java Programs', *Revis. Lect. Softw. Vis. Int. Semin.*, pp. 163–175. doi: 10.1007/3-540-45875-1.

Mei, S. W. A. N. and Cheng, A. N. G. K. (2013) 'Introducing Queuing Theory through Simulations', *9th Delta Conference on teaching and learning of undergraduate mathematics and statistics*. Kiama, Australia, (November), pp. 24–29.

Melas, C. D. *et al.* (2011) 'Modeling the acceptance of clinical information systems among hospital medical staff: An extended TAM model', *Journal of Biomedical*

Informatics, 44(4), pp. 553–564. doi: 10.1016/j.jbi.2011.01.009.

Mellar, H. and Bliss, J. (1994) 'Introduction: Modelling and Education', in Mellar, H et al. (eds) *Learning with Artificial Worlds: Computer Based Modelling in the Curriculum*. The Falmer Press, pp. 1–7.

Mellecker, R. R., Witherspoon, L. and Watterson, T. (2013) 'Active learning: Educational experiences enhanced through technology-driven active game play', *Journal of Educational Research*, 106(5), pp. 352–359. doi: 10.1080/00220671.2012.736429.

Merrill, D., Sun, E. and Kalanithi, J. (2012) 'Sifteo cubes', *Proceedings of the 2012 ACM annual conference extended abstracts on Human Factors in Computing Systems Extended Abstracts - CHI EA '12*, p. 1015. doi: 10.1145/2212776.2212374.

Meyer, H. F. and Land, R. (2006) *Overcoming Barriers to Student Understanding: Threshold concepts and troublesome knowledge*, *London and New York RoutledgeFalmer*. doi: 10.4324/9780203966273.

Meyer, J. H. F. and Land, R. (2003) 'Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines', *Improving Student Learning – Ten Years On.*, 4(1), pp. 1–16. doi: 10.1007/978-3-8348-9837-1.

Meyer, J. H. F. and Land, R. (2005) 'Threshold concepts and troublesome knowledge (2): Epistemological considerations and a conceptual framework for teaching and learning', *Higher Education*, 49(3), pp. 373–388. doi: 10.1007/s10734-004-6779-5.

Meyer, J. H. F., Land, R. and Davies, P. (2008) 'Threshold Concepts and Troublesome Knowledge (4): Issues of Variation and Variability', in *Threshold Concepts within the Disciplines*, pp. 59–74.

Miller, C. S., Settle, A. and Lalor, J. (2015) 'Learning Object-Oriented Programming in Python: Towards an Inventory of Difficulties and Testing Pitfalls', *Proceedings of the 16th Annual Conference on Information Technology Education*, pp. 59–64. doi: 10.1145/2808006.2808017.

Miniard, P. W. and Cohen, J. B. (1979) 'Isolating Attitudinal and Normative Influences in Behavioral Intentions Models', *Journal of Marketing Research*, 16(1), pp. 102–110.

doi: 10.2307/3150881.

Mitchell, T. R. *et al.* (1994) ‘Predicting self-efficacy and performance during skill acquisition.’, *Journal of Applied Psychology*, 79(4), pp. 506–517. doi: 10.1037/0021-9010.79.4.506.

Mitnik, R., Nussbaum, M. and Soto, A. (2008) ‘An autonomous educational mobile robot mediator’, *Autonomous Robots*, 25(4), pp. 367–382.

Mitrovic, A. (1998a) ‘Experiences in Implementing Constraint-Based Modeling in SQL-Tutor’, in *ITS ’98*, pp. 414–423. doi: 10.1007/3-540-68716-5_47.

Mitrovic, A. (1998b) ‘Learning SQL with a computerized tutor’, *ACM SIGCSE Bulletin*, 30(1), pp. 307–311. doi: 10.1145/274790.274318.

Mitrovic, A. (2001) ‘Investigating students’ self-assessment skills’, *User Modeling 2001*, pp. 247–250.

Mitrovic, A. (2002) ‘NORMIT: A Web-enabled tutor for database normalization’, in *Proceedings - International Conference on Computers in Education, ICCE 2002*, pp. 1276–1280. doi: 10.1109/CIE.2002.1186210.

Mitrovic, A. *et al.* (2004) ‘DB-suite: experiences with three intelligent, web-based database tutors’, *Journal of interactive learning research.* Association for the Advancement of Computing in Education, 15(4), pp. 409–432.

Mitrovic, A. (2005) ‘The Effect of Explaining on Learning: a Case Study with a Data Normalization Tutor’, in *Proceedings of ICCE 2005: the 12th International on Conference Computers in Education*, pp. 499–506.

Mitrovic, A. (2012) ‘Fifteen years of constraint-based tutors: What we have achieved and where we are going’, *User Modeling and User-Adapted Interaction*, 22(1–2), pp. 39–72. doi: 10.1007/s11257-011-9105-9.

Mitrovic, A. and Ohlsson, S. (1999) ‘Evaluation of a constraint-based tutor for a database language’, *International Journal of Artificial Intelligence in Education*, 10, pp. 238–256.

Mittal, D. *et al.* (2015) ‘CoinBeam: A tangible interface to teach money concepts to intellectually challenged children', in *Proceedings of the 7th International Conference on HCI, IndiaHCI 2015*. New York, New York, USA: ACM, pp. 116–120. doi: 10.1145/2835966.2836281.

Moghadam, A. H. and Bairamzadeh, S. (2009) 'Extending the Technology Acceptance Model for E-learning: A Case Study of Iran', in *Sixth International Conference on Information Technology: New Generations*, pp. 1659–1660. doi: 10.1109/ITNG.2009.152.

Moon, J. W. and Kim, Y. G. (2001) 'Extending the TAM for a World-Wide-Web context', *Information and Management*, 38(4), pp. 217–230. doi: 10.1016/S0378-7206(00)00061-6.

Morán, A. L. *et al.* (2013) 'Borrowing a Virtual Rehabilitation Tool for the Physical Activation and Cognitive Stimulation of Elders', in. Springer, Cham, pp. 95–102. doi: 10.1007/978-3-319-03068-5_17.

Morris, M. and Venkatesh, V. (2000) 'Age differences in technology adoption decisions: Implications for a changing work force', *Personnel Psychology*. Blackwell Publishing Ltd, 53(2), pp. 375–403. doi: 10.1111/j.1744-6570.2000.tb00206.x.

Morrison, B. B. (2015) 'Position paper: Assessing knowledge in blocks-based and text-based programming languages', in *Proceedings - 2015 IEEE Blocks and Beyond Workshop, Blocks and Beyond 2015*. IEEE, pp. 1–3. doi: 10.1109/BLOCKS.2015.7368988.

Mortenson, M. J. and Vidgen, R. (2016) 'A computational literature review of the technology acceptance model', *International Journal of Information Management*. Elsevier Ltd, 36(6), pp. 1248–1259. doi: 10.1016/j.ijinfomgt.2016.07.007.

Mosley, P. and Kline, R. (2006) 'Engaging Students: A Framework Using Lego Robotics To Teach Problem Solving', *Information Technology, Learning & Performance Journal.*, 24(1), pp. 39–45.

Mugellini, E. *et al.* (2009) 'MEMODULES as tangible shortcuts to multimedia information', in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. Springer, Berlin, Heidelberg, pp. 103–132. doi: 10.1007/978-3-642-00437-7_5.

Musa, P. F. (2006) ‘Making a case for modifying the technology acceptance model to account for limited accessibility in developing countries’, *Information Technology for Development*. Wiley Subscription Services, Inc., a Wiley company, 12(3), pp. 213–224. doi: 10.1002/itdj.20043.

Myers, I. and Briggs (1962) *The Myers-Briggs Type Indicator: Manual (1962).* Palo Alto: Consulting Psychologists Press. doi: 10.1037/14404-000.

Narita, A. (2004) ‘Development of Next-generation IP Network Design Tools Using Novel User Interface’, *NTT Technical Review*, 2(6), pp. 6–11.

Naser, S. S. A. (2008) ‘Developing visualization tool for teaching AI searching algorithms’, *Information Technology Journal*, 7(2), pp. 350–355. doi: 10.3923/itj.2008.350.355.

Nasman, J. and Cutler, B. (2013) ‘Evaluation of user interaction with daylighting simulation in a tangible user interface’, *Automation in Construction*, 36, pp. 117–127. doi: 10.1016/j.autcon.2013.08.018.

Nasri, W. and Charfeddine, L. (2012) ‘Factors affecting the adoption of Internet banking in Tunisia: An integration theory of acceptance model and theory of planned behavior’, *Journal of High Technology Management Research*, 23(1), pp. 1–14. doi: 10.1016/j.hitech.2012.03.001.

Ndubisi, N. O. (2007) ‘Evaluating the Direct and Indirect Impact of Traits and Perceptions on Technology Adoption By Women Entrepreneurs in Malaysia’, *Academy of Entrepreneurship Journal*, 13(2), pp. 1–20.

Neufert, E. (2002) *Architects’ Data*. Wiley-Blackwell.

Neulight, N. *et al.* (2007) ‘Children’s participation in a virtual epidemic in the science classroom: Making connections to natural infectious diseases’, *Journal of Science Education and Technology*. Kluwer Academic Publishers, 16(1), pp. 47–58. doi: 10.1007/s10956-006-9029-z.

Ngai, E. W. T., Poon, J. K. L. and Chan, Y. H. C. (2007) ‘Empirical examination of the adoption of WebCT using TAM’, *Computers and Education*, 48(2), pp. 250–267. doi:

10.1016/j.compedu.2004.11.007.

Nielsen, J. (1994) ‘Enhancing the explanatory power of usability heuristics’, in *Proceedings of the SIGCHI conference on Human factors in computing systems celebrating interdependence - CHI ’94*. New York, New York, USA: ACM Press, pp. 152–158. doi: 10.1145/191666.191729.

Niu, S., McCrickard, D. S. and Nguyen, S. M. (2016) ‘Learning with interactive tabletop displays’, in *Proceedings - Frontiers in Education Conference, FIE*. doi: 10.1109/FIE.2016.7757601.

Noor, M. M., Yayao, N. and Sulaiman Sumzaly (2018) ‘Effectiveness of Using Cisco Packet Tracer as a Learning Tool: A Case Study of Routing Protocol’, *International Journal of Information and Education Technology*, 8(1), pp. 11–16. doi: 10.18178/ijiet.2018.8.1.1004.

Norton, S. J., McRobbie, C. J. and Ginns, I. S. (2007) ‘Problem solving in a middle school robotics design classroom’, *Research in Science Education*, 37(3), pp. 261–277.

Novak, J. D. (1998) ‘Learning science and the science of learning’, *Studies in Science Education*, 15(1), pp. 77–101. doi: 10.1080/03057268808559949.

Novak, J. D. (2010) *Learning, creating and using knowledge: Concept maps as facilitative tools in school and corporation*, *Journal of e-Learning and knowledge society*. doi: 10.5860/CHOICE.36-1103.

NS-3 Consortium (2011) *NS-3 discrete-event network simulator*. Available at: https://www.nsnam.org/ (Accessed: 23 February 2018).

Nunes, R., Rito, F. and Duarte, C. (2015) ‘TACTIC: An API for touch and tangible interaction’, in *9th International Conference on Tangible, Embedded, and Embodied Interaction, TEI 2015*, pp. 125–132. doi: 10.1145/2677199.2680592.

Nusen, N. and Sipitakiat, A. (2012) ‘Robo-blocks: a tangible programming system with debugging for children’, in *IDC ’12 Proceedings of the 11th International Conference on Interaction Design and Children*, pp. 98–105. doi: 10.1145/2307096.2307108.

O’Malley, Claire and Fraser, D. S. (2004) *Literature Review in Learning with Tangible*

Technologies. doi: hal-00190328, version 1.

O'Malley, C. and Fraser, S. (2004) *Literature review in learning with tangible technologies*, *Halshsarchivesouvertesfr*. doi: papers2://publication/uuid/EDD99909-5D5D-4177-8916-B3C1803CFF8B.

Oechsle, R. and Schmitt, T. (2002) 'JAVAVIS: Automatic Program Visualization with Object and Sequence Diagrams Using the Java Debug Interface (JDI)', in *Software Visualization*, pp. 176–190. doi: 10.1007/3-540-45875-1.

Oh, H. *et al.* (2013) 'The digital dream lab: tabletop puzzle blocks for exploring programmatic concepts', *Tei 2013*, pp. 51–56. doi: 10.1145/2460625.2460633.

Olali, T. (2014) 'Some Impediments in the Adoption and Use of Computer Technology at the University of Nairobi', *International Journal of Humanities Social Sciences and Education*, 1(11), pp. 38–44.

Olier Quiceno, A. J., Gomez Salgado, A. A. and Caro Pineres, M. F. (2017) 'Design and Implementation of a Teaching Tool for Introduction to object-oriented programming', *IEEE Latin America Transactions*, 15(1), pp. 97–102. doi: 10.1109/TLA.2017.7827913.

Orlikowski, W. J. (2000) 'Using Technology and Constituting Structures: A Practice Lens for Studying Technology in Organizations', *Organization Science*, 11(4), pp. 404–428. doi: 10.1287/orsc.11.4.404.14600.

Overmars, M. (2005) 'Learning object-oriented design by creating games', *IEEE Potentials*, 23(5), pp. 11–13. doi: 10.1109/MP.2005.1368910.

Ozkal, K. *et al.* (2009) 'A conceptual model of relationships among constructivist learning environment perceptions, epistemological beliefs, and learning approaches', *Learning and Individual Differences*, 19(1), pp. 71–79. doi: 10.1016/j.lindif.2008.05.005.

Padilla-Meléndez, A., Del Aguila-Obra, A. R. and Garrido-Moreno, A. (2013) 'Perceived playfulness, gender differences and technology acceptance model in a blended learning scenario', *Computers and Education*, pp. 306–317. doi: 10.1016/j.compedu.2012.12.014.

Pai, F.-Y. and Huang, K.-I. (2011) 'Applying the Technology Acceptance Model to the introduction of healthcare information systems', *Technological Forecasting and Social Change*, 78(4), pp. 650–660. doi: 10.1016/j.techfore.2010.11.007.

Pan, C.-C. 'Sam', Sivo, S. and Brophy, J. (2003) 'Students' attitudes in a web-enhanced hybrid course: A structural equation modeling inquiry', *Journal of educational media & library sciences*, 41(2), pp. 181–194.

Pangaro, G. A., Maynes-Aminzade, D. and Ishii, H. (2003) 'The Actuated Workbench : 2D Actuation in Tabletop Tangible Interfaces', *Interfaces*, 4(2), pp. 181–190. doi: http://doi.acm.org/10.1145/571985.572011.

Papavlasopoulou, S., Giannakos, M. N. and Jaccheri, L. (2017) 'Reviewing the affordances of tangible programming languages: Implications for design and practice', in *IEEE Global Engineering Education Conference, EDUCON*, pp. 1811–1816. doi: 10.1109/EDUCON.2017.7943096.

Papert, S. (1983) *Mindstorms: Children, computers and powerful ideas*, *New Ideas in Psychology*. doi: 10.1016/0732-118X(83)90034-X.

Paraskeva, F., Bouta, H. and Papagianni, A. (2008) 'Individual characteristics and computer self-efficacy in secondary education teachers to integrate technology in educational practice', *Computers and Education*, 50(3), pp. 1084–1091. doi: 10.1016/j.compedu.2006.10.006.

Park, N., Lee, K. M. and Cheong, P. H. (2007) 'University instructors' acceptance of electronic courseware: An application of the technology acceptance model', *Journal of Computer-Mediated Communication*, 13(1), pp. 163–186. doi: 10.1111/j.1083-6101.2007.00391.x.

Park, S. Y. *et al.* (2009) 'An Analysis of the Technology Acceptance Model in Understanding University Students' Behavioral Intention to Use e-Learning', *Journal of Educational Technology & Society*. International Forum of Educational Technology & Society, 12(3), pp. 150–162. doi: 10.2307/jeductechsoci.12.3.150.

Park, Y., Son, H. and Kim, C. (2012) 'Investigating the determinants of construction professionals' acceptance of web-based training: An extension of the technology acceptance model', in *Automation in Construction*, pp. 377–386. doi: 10.1016/j.autcon.2011.09.016.

Parker, I. (1994) 'Reflexive research and the grounding of analysis: Social psychology and the psy-complex', *Journal of Community & Applied Social Psychology*. John Wiley & Sons, Ltd, 4(4), pp. 239–252. doi: 10.1002/casp.2450040404.

Parsons, S. (2004) 'Teaching ai using lego MindStorms', *Accessible Hands-on AI and Robotics Education:*

Pashler, H. *et al.* (2008) 'Learning Styles: Concepts and Evidence', *Psychological Science in the Public Interest*, 9(3), pp. 105–119. doi: 10.1111/j.1539-6053.2009.01038.x.

Patten, J. *et al.* (2001) 'Sensetable: A Wireless Object Tracking Platform for Tangible User Interfaces', *Proceedings of the SIGCHI conference on Human factors in computing systems*. New York, New York, USA: ACM Press, pp. 253–260. doi: http://doi.acm.org/10.1145/365024.365112.

Patten, J., Griffith, L. and Ishii, H. (2000) 'A tangible interface for controlling robotic toys', *CHI '00: CHI '00 extended abstracts on Human factors in computing systems*, pp. 277–278. doi: http://doi.acm.org/10.1145/633292.633454.

Patten, J. and Ishii, H. (2007) 'Mechanical constraints as computational constraints in tabletop tangible interfaces', *Proceedings of the SIGCHI conference on Human factors in computing systems CHI 07*, p. 809. doi: 10.1145/1240624.1240746.

Patten, J., Recht, B. and Ishii, H. (2002) 'Audiopad: A Tag-based Interface for Musical Performance', in *Proceedings of the Conference on New Interfaces for Musical Expression (NIME'02)*, pp. 1–6.

Patton, M. (1990) *Qualitative Evaluation and Research Methods*, *Qualitative Evaluation and Research Methods*. Beverly HIlls, California: Sage Publications. doi: 10.1002/nur.4770140111.

Patton, M. Q. (2002) *Qualitative research and evaluation methods*. Sage Publications.

Pavlou, P. (2003) 'Consumer Acceptance of Electronic Commerce: Integrating Trust and Risk with the Technology Acceptance Model', *International Journal of Electronic*

Commerce, 7(3), pp. 101–134. doi: 10.1.1.86.7139.

Perdos, A., Chatzigeorgiou, A. and Stephanides, G. (2004) 'Teaching queuing systems modeling using UML', in *Proceedings - IEEE International Conference on Advanced Learning Technologies, ICALT 2004*, pp. 795–797. doi: 10.1109/ICALT.2004.1357660.

Perkins, D. (1999) 'The Many Faces of Constructivism', *Educational Leadership*, 57(3), pp. 6–11.

Perlman, R. (1974) 'TORTIS (Toddler's Own Recursive Turtle Interpreter System).'

Perlman, R. (1976) 'Using Computer Technology to Provide a Creative Learning Environment for Preschool Children', *MIT Logo Memo #24,* pp. 1–13.

Petcu, D. *et al.* (2013) 'Integrating Cisco Packet Tracer with Moodle platform: Support for teaching and automatic evaluation', in *Proceedings - RoEduNet IEEE International Conference*. doi: 10.1109/RoEduNet.2013.6714190.

Piper, B., Ratti, C. and Ishii, H. (2002) 'Illuminating Clay : A 3-D Tangible Interface for Landscape Analysis', *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '02*, (1), pp. 355–362. doi: 10.1145/503376.503439.

van de Pol, J., Volman, M. and Beishuizen, J. (2010) 'Scaffolding in teacher-student interaction: A decade of research', *Educational Psychology Review*, pp. 271–296. doi: 10.1007/s10648-010-9127-6.

Poulson, B. (2016) *Artificial neural networks*. Available at: https://www.lynda.com/Big-Data-tutorials/Artificial-neural-networks/420305/505154-4.html (Accessed: 26 September 2017).

Preece, J., Rogers, Y. and Sharp, H. (2015) *Interaction Design: Beyond Human-Computer Interaction*. 4th Editio, *Design*. 4th Editio. doi: 10.1162/leon.2005.38.5.401.

Prensky, M. and Marc (2003) 'Digital game-based learning', *Computers in Entertainment*. ACM, 1(1), p. 21. doi: 10.1145/950566.950596.

Price, S. *et al.* (2003) 'Using "tangibles" to promote novel forms of playful learning', *Interacting with Computers*, 15(2 SPEC.), pp. 169–185. doi: 10.1016/S0953-

5438(03)00006-7.

Price, S. *et al.* (2008) ‘Towards a framework for investigating tangible environments for learning’, *International Journal of Arts and Technology*, 1(3/4), p. 351. doi: 10.1504/IJART.2008.022367.

Price, S. *et al.* (2009) ‘Technology and embodiment: Relationships and implications for knowledge, creativity and communication’, *Beyond Current Horizons*. Department for Children, Schools and Families & Futurelab, (May), pp. 1–22.

Price, S. and Rogers, Y. (2004) ‘Let’s get physical: The learning benefits of interacting in digitally augmented physical spaces’, *Computers and Education*, 43(1-2 SPEC ISS.), pp. 137–151. doi: 10.1016/j.compedu.2003.12.009.

Prince, M. (2004) ‘Does active learning work? A review of the research’, *Journal of Engineering Education*, 93(3), pp. 223–232. doi: 10.1002/j.2168-9830.2004.tb00809.x.

Psycharis, S. (2016) ‘Inquiry based-computational experiment, acquisition of threshold concepts and argumentation in science and mathematics education’, *Educational Technology and Society*, 19(3), pp. 282–293.

Purnomo, S. H. and Lee, Y. H. (2013) ‘E-learning adoption in the banking workplace in Indonesia: An empirical study’, *Information Development*, 29(2), pp. 138–153. doi: 10.1177/0266666912448258.

Qi, J., Demir, A. and Paradiso, J. A. (2017) ‘Code Collage: Tangible Programming On Paper With Circuit Stickers’, in *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA ’17*. New York, New York, USA: ACM Press, pp. 1970–1977. doi: 10.1145/3027063.3053084.

Qi, Y. *et al.* (2015) ‘TanProStory : A Tangible Programming System for Children’s Storytelling’, in *Chi 2015*, pp. 1001–1006. doi: 10.1145/2702613.2732806.

Quarles, J. *et al.* (2008) ‘Tangible User Interfaces Compensate for Low Spatial Cognition’, in *2008 IEEE Symposium on 3D User Interfaces*. IEEE, pp. 11–18. doi: 10.1109/3DUI.2008.4476585.

Quigley, M. *et al.* (2009) ‘ROS: an open-source Robot Operating System’, *Icra*, 3(Figure 1), p. 5.

Raffle, H. *et al.* (2007) 'Jabberstamp: embedding sound and voice in traditional drawings', *Proceedings of the 6th …*, pp. 137–144. doi: 10.1145/1297277.1297306.

Raffle, H. S., Parkes, A. J. and Ishii, H. (2004) 'Topobo: a constructive assembly system with kinetic memory', *System*, 6(1), pp. 647–654. doi: 10.1145/985692.985774.

Ragsdale, C. (2010) *Spreadsheet Modeling & Decision Analysis: A Practical Introduction to Management Science*. South Western, Cengage Learning. doi: 10.1017/CBO9781107415324.004.

Rahman, A. A. *et al.* (2015) 'Emerging project based learning in flipped classroom: Technology used to increase students' engagement', in *3rd International Conference on Information and Communication Technology, ICoICT 2015*, pp. 212–215. doi: 10.1109/ICoICT.2015.7231424.

Rai, A. and Bajwa, D. S. (1997) 'An Empirical Investigation into Factors Relating to the Adoption of Executive Information Systems: An Analysis of EIS for Collaboration and Decision Support', *Decision Sciences*, 28(4), pp. 939–974. doi: 10.1111/j.1540-5915.1997.tb01337.x.

Rai, A., Lang, S. S. and Welker, R. B. (2002) 'Assessing the validity of IS success models: An empirical test and theoretical analysis', *Information Systems Research*, 13(1), pp. 50–69. doi: 10.1287/isre.13.1.50.96.

Rai, A. and Patnayakuni, R. (1996) 'A Structural Model for CASE Adoption Behavior', *Journal of Management Information Systems*, 13(2), pp. 205–234. doi: 10.1080/07421222.1996.11518129.

Ram, S. (2008) 'Teaching Data Normalization: Traditional Classroom Methods versus Online Visual Methods – a Literature Review', *Reproduction*.

Rambe, P. and Nel, L. (2015) 'Technological utopia, dystopia and ambivalence: Teaching with social media at a South African university', *British Journal of Educational Technology*, 46(3), pp. 629–648. doi: 10.1111/bjet.12159.

Randelli, G., Venanzi, M. and Nardi, D. (2011) 'Tangible interfaces for robot teleoperation', *Proceedings of the 6th international conference on Human-robot interaction - HRI '11*, p. 231. doi: 10.1145/1957656.1957746.

Ras, E. *et al.* (2013) 'Empirical studies on a tangible user interface for technology-based assessment : Insights and emerging challenges', *International Journal of e-Assessment*, 3(1), pp. 1–19.

Ras, E. *et al.* (2014) 'Moving towards the assessment of collaborative problem solving skills with a tangible user interface', *Turkish Online Journal of Educational Technology*, 13(4), pp. 95–104.

Rauniar, R. *et al.* (2014) 'Technology acceptance model (TAM) and social media usage: an empirical study on Facebook', *Journal of Enterprise Information Management*. Edited by D. Chris Evans and Professor Raymond H. Emerald Group Publishing Limited, 27(1), pp. 6–30. doi: 10.1108/JEIM-04-2012-0011.

Rauterberg, M. *et al.* (1998) 'BUILD-IT: a planning tool for construction and design', in *CHI 98 conference summary on Human factors in computing systems*, pp. 177–178. doi: http://doi.acm.org/10.1145/286498.286657.

Redish, E. F. (1994) 'Implications of cognitive studies for teaching physics', *American Journal of Physics*, 62(9), pp. 796–803. doi: 10.1119/1.17461.

Redström, J. (2008) 'Tangled interaction', *ACM Transactions on Computer-Human Interaction*, 15(4), pp. 1–17. doi: 10.1145/1460355.1460358.

Reed, J. H. (1980) 'Computer Simulation: A Tool to Teach Queuing Theory', *Developments in Business Simulation and Experiential Learning: Proceedings of the Annual ABSEL conference*, 7(0).

Reed, M. W. and Overbaugh, R. C. (1993) 'The Effects of Prior Experience and Instructional Format on Teacher Education Students' Computer Anxiety and Performance.', *Computers in the Schools*. Taylor & Francis Group, pp. 75–90. doi: 10.1300/J025v09n02_08.

Rekimoto, J., Ullmer, B. and Oba, H. (2001) 'DataTiles: a modular platform for mixed physical and graphical interactions', *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 269–276. doi: 10.1145/365024.365115.

Resnick, M. *et al.* (1996) 'Programmable Bricks: Toys to think with', *IBM Systems Journal*, 35(Figure 1), pp. 443–452. doi: 10.1147/sj.353.0443.

Resnick, M. *et al.* (2009) 'Scratch: programming for all', *Communications of the ACM*. ACM, 52(11), p. 60. doi: 10.1145/1592761.1592779.

Resnick, M. and Wilensky, U. (1998) 'Diving into complexity: Developing probabilistic decentralized thinking through role-playing activities', *Journal of the Learning Sciences*, 7(2), pp. 153–172. doi: 10.1207/s15327809jls0702_1.

Resta, P. and Laferrière, T. (2007) 'Technology in support of collaborative learning', *Educational Psychology Review*. Kluwer Academic Publishers-Plenum Publishers, pp. 65–83. doi: 10.1007/s10648-007-9042-7.

Rhodes, W. (2012) 'Meta-Analysis: An Introduction Using Regression Models', *Evaluation Review*, 36(1), pp. 24–71. doi: 10.1177/0193841X12442673.

Ribeiro, P., Simoes, H. and Ferreira, M. (2009) 'Teaching Artificial Intelligence and Logic Programming in a Competitive Environment', *Informatics in Education*, 8(1), pp. 85–100.

Ricardo A. Corredor (2008) *InfoViz & Interaction*. Available at: https://sites.google.com/site/racorredor/projects/infoviz-interaction (Accessed: 23 February 2017).

Rieser, J. J., Garing, A. E. and Young, M. F. (1994) 'Imagery, Action, and Young Children's Spatial Orientation: It's Not Being There That Counts, It's What One Has in Mind', *Child Development*, 65(5), pp. 1262–1278. doi: 10.1111/j.1467-8624.1994.tb00816.x.

Ringwood, J. V. and Galvin, G. (2002) 'Computer-aided learning in artificial neural networks', *IEEE Transactions on Education*, 45(4), pp. 380–387. doi: 10.1109/TE.2002.804401.

Roberto, R. A. *et al.* (2013) 'A dynamic blocks platform based on projective augmented reality and tangible interfaces for educational activities', in *Proceedings - 2013 15th Symposium on Virtual and Augmented Reality, SVR 2013*, pp. 1–9. doi: 10.1109/SVR.2013.11.

Rodríguez Corral, J. M. *et al.* (2014) ‘A game-based approach to the teaching of object-oriented programming languages’, *Computers & Education*. Elsevier Ltd, 73, pp. 83–92. doi: 10.1016/j.compedu.2013.12.013.

Rogers, Y. *et al.* (2002) ‘A conceptual framework for mixed reality environments: Designing novel learning activities for young children’, *Presence*, 11(6), pp. 677–686. doi: 10.1162/105474602321050776.

Rogers, Y. and Muller, H. (2006) ‘A framework for designing sensor-based interactions to promote exploration and reflection in play’, *International Journal of Human Computer Studies*, 64(1), pp. 1–14. doi: 10.1016/j.ijhcs.2005.05.004.

Roldan-Alvarez, D. *et al.* (2014) ‘Benefits of combining multitouch tabletops and turn-based collaborative learning activities for people with cognitive disabilities and people with ASD’, in *Proceedings - IEEE 14th International Conference on Advanced Learning Technologies, ICALT 2014*, pp. 566–570. doi: 10.1109/ICALT.2014.166.

Rosenshine, B. and Meister, C. (1992) ‘The Use of Scaffolds for Teaching Higher-Level Cognitive Strategies’, *Educational Leadership*, 49(7), pp. 26–33.

Rountree, J. and Rountree, N. (2009) ‘Issues regarding threshold concepts in computer science’, in *Proceedings of the Eleventh Australasian Conference on Computing Education - Volume 95*. Australian Computer Society, Inc., pp. 139–146.

Russell, I. and Markov, Z. (2009) ‘A multi-institutional project-centric framework for teaching AI concepts’, in *Proceedings - Frontiers in Education Conference, FIE*. doi: 10.1109/FIE.2009.5350408.

Ryan, A. (2006) ‘Post-Positivist Approaches to Research’, *Researching and Writing your thesis: a guide for postgraduate students*.

Ryan, R. M. and Deci, E. L. (2000) ‘Intrinsic and Extrinsic Motivations: Classic Definitions and New Directions’, *Contemporary Educational Psychology*, 25(1), pp. 54–67. doi: 10.1006/ceps. 1999.1020.

Ryokai, K. and Cassell, J. (1999) ‘StoryMat: a play space for collaborative storytelling’, *CHI’99 extended abstracts on Human factors in …*, (May), pp. 272–273. doi: 10.1145/632716.632883.

Ryokai, K., Marti, S. and Ishii, H. (2004) 'I/O brush: drawing with everyday objects as ink', in *Proceedings of the 2004 conference on Human factors in computing systems - CHI '04*. New York, New York, USA: ACM Press, pp. 303–310. doi: 10.1145/985692.985731.

Saga, V. L. and Zmud, R. W. (1994) 'The Nature and Determinants of It Acceptance, Routinization, and Infusion', in *Diffusion, Transfer and Implementation of Information Technology*, pp. 67–86.

Sánchez-Prieto, J. C., Olmos-Migueláñez, S. and García-Peñalvo, F. J. (2016) 'Informal tools in formal contexts: Development of a model to assess the acceptance of mobile technologies among teachers', *Computers in Human Behavior*, 55, pp. 519–528. doi: 10.1016/j.chb.2015.07.002.

Sánchez-Prieto, J. C., Olmos-Migueláñez, S. and García-Peñalvo, F. J. (2017) 'MLearning and pre-service teachers: An assessment of the behavioral intention using an expanded TAM model', *Computers in Human Behavior*. Pergamon, 72, pp. 644–654. doi: 10.1016/j.chb.2016.09.061.

Sandrasegaran, K. and Trieu, M. (2006) 'Inetwork: An Interactive Learning Tool for Communication Networks', in *Tools for Teaching Computer Networking and Hardware Concepts*. IGI Global, pp. 39–61. doi: 10.4018/978-1-59140-735-5.ch003.

Sapounidis, T. and Demetriadis, S. (2013) 'Tangible versus graphical user interfaces for robot programming: exploring cross-age children's preferences', *Personal and Ubiquitous Computing*. Springer London, 17(8), pp. 1775–1786. doi: 10.1007/s00779-013-0641-7.

Sapounidis, T., Demetriadis, S. and Stamelos, I. (2015) 'Evaluating children performance with graphical and tangible robot programming tools', *Personal and Ubiquitous Computing*, 19(1), pp. 225–237. doi: 10.1007/s00779-014-0774-3.

Sarkar, N. I. (2008) 'An Interactive Tool for Teaching and Learning LAN Design', in *Information Communication Technologies*. IGI Global, pp. 1726–1740. doi: 10.4018/978-1-59904-949-6.ch122.

Sarkar, N. I. and Petrova, K. (2011) 'Design and Evaluation of a Web-Based Tool for

Teaching Computer Network Design to Undergraduates', *International Journal of Web-Based Learning and Teaching Technologies*, 6(4), pp. 39–59. doi: 10.4018/jwltt.2011100103.

Sarker, Saonee, Valacich, J. S. and Sarker, Suprateek (2005) 'Technology Adoption by Groups: A Valence Perspective', *Journal of the Association for Information Systems*, 6(2), pp. 37–71.

Scaife, M. and Rogers, Y. (1996) 'External cognition: How do graphical representations work?', *International Journal of Human Computer Studies*, 45(2), pp. 185–213. doi: 10.1006/ijhc.1996.0048.

Scarlatos, L. L., Dushkina, Y. and Landy, S. (1999) 'TICLE: a tangible interface for collaborative learning environments', in *CHI '99 extended abstracts on Human factors in computing systems - CHI '99*. New York, New York, USA: ACM Press, p. 260. doi: 10.1145/632716.632876.

Scharf, F. *et al.* (2012) 'Tangicons 3.0: An Educational Non-competitive Collaborative Game', *Proceedings of the 11th International Conference on Interaction Design and Children*, pp. 144–151. doi: 10.1145/2307096.2307113.

Scherer, R. *et al.* (2018) 'The importance of attitudes toward technology for pre-service teachers' technological, pedagogical, and content knowledge: Comparing structural equation modeling approaches', *Computers in Human Behavior*. Elsevier Science Publishers B. V., 80(C), pp. 67–80. doi: 10.1016/j.chb.2017.11.003.

Schneider, B. *et al.* (2011) 'Benefits of a tangible interface for collaborative learning and interaction', *IEEE Transactions on Learning Technologies*, 4(3), pp. 222–232. doi: 10.1109/TLT.2010.36.

Schneider, B. *et al.* (2012) 'BrainExplorer: an innovative tool for teaching neuroscience', *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*, pp. 407–410. doi: 10.1145/2396636.2396712.

Schneider, B. *et al.* (2013) 'Preparing for Future Learning with a Tangible User Interface: The Case of Neuroscience', *IEEE Transactions on Learning Technologies*, 6(2), pp. 117–129. doi: 10.1109/TLT.2013.15.

Schneider, B. *et al.* (2016) 'Using Mobile Eye-Trackers to Unpack the Perceptual Benefits of a Tangible User Interface for Collaborative Learning', *ACM Transactions on Computer-Human Interaction*, 23(6), pp. 39–62. doi: 10.1145/3012009.

Schneider, B. (2017) 'Preparing Students for Future Learning with Mixed Reality Interfaces', in. Springer, Singapore, pp. 219–236. doi: 10.1007/978-981-10-5490-7_12.

Schneider, B. and Blikstein, P. (2013) 'Supporting Collaborative Learning of Probabilities with a Tangible User Interface: Design and Preliminary Results', in *American Educational Research Association Conference, AERA '2013.* San Francisco, pp. 1–5.

Schneider, B. and Blikstein, P. (2015) 'Unraveling Students' Interaction Around a Tangible Interface using Multimodal Learning Analytics', *JEDM - Journal of Educational Data Mining*. International Educational Data Mining Soc, 7(3), pp. 89–116.

Schneider, B. and Blikstein, P. (2016) 'Flipping the Flipped Classroom: A Study of the Effectiveness of Video Lectures Versus Constructivist Exploration Using Tangible User Interfaces', *IEEE Transactions on Learning Technologies*, 9(1), pp. 5–17. doi: 10.1109/TLT.2015.2448093.

Schneider, B., Blikstein, P. and Mackay, W. (2012) 'Combinatorix: Tangible user interface that supports collaborative learning of probabilities', *ITS '12 Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*. New York, New York, USA: ACM Press, pp. 129–132. doi: 10.1145/2396636.2396656.

Scholtz, B. *et al.* (2016) 'Does usability matter? An analysis of the impact of usability on technology acceptance in ERP settings', *Interdisciplinary Journal of Information, Knowledge, and Management*, 11(11), pp. 309–330. doi: 10.28945/3591.

Schön, D. A. (1987) *Educating the reflective practitioner : toward a new design for teaching and learning in the professions*. Jossey-Bass.

Schubert, G. (2016) *COLLABORATIVE DESIGN PLATFORM*. Available at: http://cdp.ai.ar.tum.de/project (Accessed: 23 February 2017).

Schubert, M., Serna, A. and George, S. (2012) 'Using Collaborative Activities on

Tabletops to Enhance Learning and Knowledge Transfer', in *2012 IEEE 12th International Conference on Advanced Learning Technologies*, pp. 610–612. doi: 10.1109/ICALT.2012.73.

Schweikardt, E. *et al.* (2009) 'A tangible construction kit for exploring graph theory', *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*. New York, New York, USA: ACM Press, pp. 373–376. doi: 10.1145/1517664.1517739.

Schweppe, J. and Rummer, R. (2014) 'Attention, Working Memory, and Long-Term Memory in Multimedia Learning: An Integrated Perspective Based on Process Models of Working Memory', *Educational Psychology Review*, pp. 285–306. doi: 10.1007/s10648-013-9242-2.

Sears, A. and Jacko, J. A. (2008) *The Human-Computer Interaction Handbook. Fundamentals, evolving technologies and emerging applications*, *Lawrence Erlbaum Associates*. doi: 10.1201/9781410615862.

Seffah, A. *et al.* (2006) 'Usability measurement and metrics: A consolidated model', *Software Quality Journal*, 14(2), pp. 159–178. doi: 10.1007/s11219-006-7600-8.

Seng, W. Y. and Yatim, M. H. M. (2014) 'Computer Game as Learning and Teaching Tool for Object Oriented Programming in Higher Education Institution', *Procedia - Social and Behavioral Sciences*. Elsevier, 123, pp. 215–224. doi: 10.1016/J.SBSPRO.2014.01.1417.

Serenko, A. (2008) 'A model of user adoption of interface agents for email notification', *Interacting with Computers*, 20(4–5), pp. 461–472. doi: 10.1016/j.intcom.2008.04.004.

Seroka, S. F. (1999) *Implementation of affirmative action in schools: A teacher's perspective*. University of Johannesburg.

Service, O. *et al.* (2014) 'EAST Four simple ways to apply behavioural insights', *Nesta*, p. 53. doi: http://behaviouralinsights.co.uk/publications/east-four-simple-ways-apply-behavioural-insights.

Severiens, S., Meeuwisse, M. and Born, M. (2015) 'Student experience and academic success: comparing a student-centred and a lecture-based course programme', *Higher Education*, 70(1). doi: 10.1007/s10734-014-9820-3.

Shaer, O. *et al.* (2004) 'The TAC paradigm: Specifying tangible user interfaces', *Personal and Ubiquitous Computing*, 8(5), pp. 359–369. doi: 10.1007/s00779-004-0298-3.

Shaer, O. *et al.* (2010) 'G-nome Surfer : a Tabletop Interface for Collaborative Exploration of Genomic Data', *Human-Computer Interaction*, pp. 1427–1436. doi: 10.1145/1753326.1753539.

Shaer, O. *et al.* (2014) 'Designing reality-based interfaces for experiential bio-design', *Personal and Ubiquitous Computing*, 18(6), pp. 1515–1532. doi: 10.1007/s00779-013-0752-1.

Shaer, O., Horn, M. S. and Jacob, R. J. K. (2009) 'Tangible user interface laboratory: Teaching tangible interaction design in practice', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 23(03), p. 251. doi: 10.1017/S0890060409000225.

Shaer, O. and Hornecker, E. (2009) 'Tangible User Interfaces: Past, Present, and Future Directions', *Foundations and Trends® in Human–Computer Interaction*, 3(1–2), pp. 1–137. doi: 10.1561/1100000026.

Shaer, O. and Jacob, R. J. K. (2009) 'A Specification Paradigm for the Design and Implementation of Tangible User Interfaces', *ACM Transactions on Computer-Human Interaction*, 16(4), pp. 20:1--20:38. doi: 10.1145/1614390.1614395.

Shanmugam, V. *et al.* (2011) 'Enhance student's learning with an aid of simulation software to understand Computer Networking Undergraduate courses.', in *Enhancing Learning: Teaching & Learning Conference*.

SharkTime Software (2013) *Sharky Neural Network - Classification neural network in action*. Available at: http://sharktime.com/us_SharkyNeuralNetwork.html (Accessed: 26 September 2017).

Sharlin, E. *et al.* (2002) 'Cognitive cubes: a tangible user interface for cognitive assessment', *Proceedings of the SIGCHI conference on Human factors in computing systems*, (4), pp. 347–354. doi: 10.1145/503376.503438.

Sharlin, E. *et al.* (2004) 'On tangible user interfaces, humans and spatiality', *Personal and Ubiquitous Computing*, 8(5), pp. 338–346. doi: 10.1007/s00779-004-0296-5.

Sharlin, E. *et al.* (2009) 'A tangible user interface for assessing cognitive mapping ability', *International Journal of Human Computer Studies*, 67(3), pp. 269–278. doi: 10.1016/j.ijhcs.2008.09.014.

Sharp, J. H. (2007) 'Development, Extension, and Application : A Review of the Technology Acceptance Model', *Information Systems Education Journal*, 5(9), pp. 1–11.

Sheetz, S. D. *et al.* (1997) 'Exploring the Difficulties of Learning Object-Oriented Techniques', *Journal of Management Information Systems*, 14(2), pp. 103–131. doi: 10.1080/07421222.1997.11518167.

Shen, C. *et al.* (2004) 'DiamondSpin: an extensible toolkit for around-the-table interaction', *Architecture*, 6(1), pp. 167–174. doi: 10.1145/985692.985714.

Shen, J. and Eder, L. B. (2009) 'Intentions to Use Virtual Worlds for Education', *Journal of Information Systems Education*, 20(2), pp. 225–234.

Shene, C. (1998) 'Multithreaded programming in an introduction to operating systems course', *ACM SIGCSE Bulletin*. Atlanta, Georgia. doi: 10.1145/274790.274305.

Sheridan, J. *et al.* (2009) 'DIY Design Process for Interactive Surfaces', *HCI 2009 – People and Computers XXIII – Celebrating people and technology*, pp. 485–493.

Sherstyuk, A., Treskunov, A. and Berg, B. (2009) 'Semi-Automatic Surface Scanner for Medical Tangible User Interfaces', *International Journal of Image and Graphics*, 10(2), pp. 219–233. doi: 10.1142/S0219467810003743.

Shih, H. P. (2004) 'Extended technology acceptance model of Internet utilization behavior', *Information and Management*, pp. 719–729. doi: 10.1016/j.im.2003.08.009.

Shiratuddin, N. and Landoni, M. (2002) 'Evaluation of content activities in children's educational software', *Evaluation and Program Planning*, 25(2), pp. 175–182. doi: 10.1016/S0149-7189(02)00011-3.

Shneiderman, B. (2010) 'The Eight Golden Rules of Interface Design', in

Shneiderman, B and Plaisant, C. (eds) *Designing the User Interface: Strategies for Effective Human-Computer Interaction*. Fifth Edit, p. 606.

Simon, M. (2011) *The Role of the Researcher*.

Singh, S. and Riedel, S. (2016) 'Creating Interactive and Visual Educational Resources for AI', *Proceedings of the 30th Conference on Artificial Intelligence (AAAI 2016)*, pp. 4101–4106.

Sirowy, S. *et al.* (2009) 'Virtual microcontrollers', *ACM SIGBED Review*. ACM, 6(1), pp. 1–8. doi: 10.1145/1534480.1534486.

Sitdhisanguan, K. *et al.* (2008) 'Evaluation the Efficacy of Computer - Based Training Using Tangible User Interface for Low-Function Children with Autism', in *2008 Second IEEE International Conference on Digital Game and Intelligent Toy Enhanced Learning*. IEEE, pp. 70–74. doi: 10.1109/DIGITEL.2008.28.

Sitdhisanguan, K. *et al.* (2012) 'Using tangible user interfaces in computer-based training systems for low-functioning autistic children', *Personal and Ubiquitous Computing*, 16(2), pp. 143–155. doi: 10.1007/s00779-011-0382-4.

Sivasakthi, M. and Rajendran, R. (2011) 'Learning difficulties of "object-oriented programming paradigm using Java": Students' perspective', *Indian Journal of Science and Technology*, 4(8), pp. 983–985. doi: 10.17485/ijst/2011/v4i8/30906.

Skulmowski, A. *et al.* (2016) 'Embodied learning using a tangible user interface: The effects of haptic perception and selective pointing on a spatial learning task', *Computers and Education*, 92–93, pp. 64–75. doi: 10.1016/j.compedu.2015.10.011.

Skulmowski, A. and Rey, G. D. (2017) 'Bodily effort enhances learning and metacognition: Investigating the relation between physical effort and cognition using dual-process models of embodiment', *Advances in Cognitive Psychology*, 13(1), pp. 3–10. doi: 10.5709/acp-0202-9.

Sluis, R. J. W. *et al.* (2004) 'Read-It: five-to-seven-year-old children learn to read in a tabletop environment', in *Proceeding of the 2004 conference on Interaction design and children building a community - IDC '04*. New York, New York, USA: ACM Press, pp. 73–80. doi: 10.1145/1017833.1017843.

Smilkov, D. and Carter, S. (2017) ‘A Neural Network Playground’. TensorFlow.

Smith, A. (2011) ‘Classroom-based Multi-player Network Simulation Experiences of interactive scenarios using Packet Tracer’, *ICNS 2011, The Seventh International Conference on Networking and Services*, (c), pp. 306–309.

Smith, P. L. and Ragan, T. J. (2005) *Instructional design*. 3rd edn. J. Wiley & Sons.

Soliman, O. S. and Elgendi, E. A. (2014) ‘Recent Developments of Computational Intelligence for Resource Constrained Project Scheduling Problems: A Taxonomy and Review’, *International Journal of Advanced Research in Computer Science and Software Engineering*, 4(8), pp. 2277–128.

Son, H. *et al.* (2012) ‘Toward an understanding of construction professionals’ acceptance of mobile computing devices in South Korea: An extension of the technology acceptance model’, *Automation in Construction*, 28, pp. 82–90. doi: 10.1016/j.autcon.2012.07.002.

Song, H. S. *et al.* (2014) ‘The cognitive impact of interactive design features for learning complex materials in medical education’, *Computers & Education*, 71, pp. 198–205. doi: 10.1016/j.compedu.2013.09.017.

Sorathia, K. and Servidio, R. (2012) ‘Learning and Experience: Teaching Tangible Interaction & Edutainment’, *Procedia - Social and Behavioral Sciences*, 64, pp. 265–274. doi: 10.1016/j.sbspro.2012.11.031.

Šorgo, A. *et al.* (2017) ‘Attributes of digital natives as predictors of information literacy in higher education’, *British Journal of Educational Technology*, 48(3), pp. 749–767. doi: 10.1111/bjet.12451.

Speier, C., Vessey, I. and Valacich, J. S. (2003) ‘The Effects of Interruptions, Task Complexity, and Information Presentation on Computer-Supported Decision-Making Performance’, *Decision Sciences*. Wiley/Blackwell (10.1111), 34(4), pp. 771–797. doi: 10.1111/j.1540-5414.2003.02292.x.

Spreicer, W. (2011) ‘Tangible interfaces as a chance for higher technology acceptance by the elderly’, *Proceedings of the 12th International Conference on Computer Systems and Technologies - CompSysTech ’11*, p. 311. doi:

10.1145/2023607.2023660.

Stanislaw, P. *et al.* (2016) ‘State Model Diagrams for Teaching Networking – a SOLO Based Evaluation’, *Modern Applied Science*, 10(10), p. 231. doi: 10.5539/mas.v10n10p231.

Stanton, D. *et al.* (2001) ‘Classroom collaboration in the design of tangible interfaces for storytelling’, *the SIGCHI conference*, (3), pp. 482–489. doi: 10.1145/365024.365322.

Starcic, A. I., Cotic, M. and Zajc, M. (2013) ‘Design-based research on the use of a tangible user interface for geometry teaching in an inclusive classroom’, *British Journal of Educational Technology*, 44(5), pp. 729–744. doi: 10.1111/j.1467-8535.2012.01341.x.

SteelHead (2017) ‘OPNET Riverbed Modeler’.

Stolterman, E. and Wiberg, M. (2010) ‘Concept-driven interaction design research’, *Human-Computer Interaction*, 25(2), pp. 95–118. doi: 10.1080/07370020903586696.

Strawhacker, A. and Bers, M. U. (2015) ‘“I want my robot to look for food”: Comparing Kindergartner’s programming comprehension using tangible, graphic, and hybrid user interfaces’, *International Journal of Technology and Design Education*, 25(3), pp. 293–319. doi: 10.1007/s10798-014-9287-7.

Strawhacker, A., Sullivan, A. and Bers, M. U. (2013) ‘TUI, GUI, HUI: Is a bimodal interface truly worth the sum of its parts?’, in *Proceedings of the 12th International Conference on Interaction Design and Children*, pp. 309–312. doi: 10.1145/2485760.2485825.

Stringer, M. *et al.* (2004) ‘Teaching Rhetorical Skills with a Tangible User Interface’, *Screen*, 44(0), pp. 11–18. doi: 10.1145/1017833.1017835.

Sugar, W. A. (2001) ‘What is so good about user-centered design? Documenting the effect of usability sessions on novice software designers’, *Journal of Research on Computing in Education*, 33(3), pp. 235–250. doi: 10.1080/08886504.2001.10782312.

Sullivan, A., Bers, M. and Pugnali, A. (2017) ‘The Impact of User Interface on Young Children’s Computational Thinking’, *Journal of Information Technology Education:*

Innovations in Practice. Informing Science Institute, 16, pp. 171–193.

Sullivan, A., Elkin, M. and Bers, M. U. (2015) 'KIBO Robot Demo: Engaging Young Children in Programming and Engineering', *Proceedings of the 14th International Conference on Interaction Design and Children - IDC '15*, pp. 418–421. doi: 10.1145/2771839.2771868.

Šumak, B., Heričko, M. and Pušnik, M. (2011) 'A meta-analysis of e-learning technology acceptance: The role of user types and e-learning technology types', *Computers in Human Behavior*, pp. 2067–2077. doi: 10.1016/j.chb.2011.08.005.

Sun, H. and Zhang, P. (2006) 'Causal Relationships between Perceived Enjoyment and Perceived Ease of Use: An Alternative Approach', *Journal of the Association for Information Systems*, 7(9), pp. 618–645. doi: 10.1016/j.chb.2010.06.020.

Sun, X. *et al.* (2015) 'Efficient event detection in social media data streams', *15th IEEE International Conference on Computer and Information Technology, CIT 2015, 14th IEEE International Conference on Ubiquitous Computing and Communications, IUCC 2015, 13th IEEE International Conference on Dependable, Autonomic and Secure Computing*, pp. 1711–1717. doi: 10.1109/CIT/IUCC/DASC/PICOM.2015.258.

Sundaravej, T. (2004) 'Empirical Validation of Unified Theory of Acceptance and Use of Technology Model', *Journal of Global Information Technology Management*, 13(1), pp. 5–27.

Suraweera, P. and Mitrovic, A. (2002) 'KERMIT: A constraint-based tutor for database modeling', *Proceedings of the 6th International Conference on Intelligent Tutoring Systems*, 2363, pp. 377–387. doi: 10.1007/3-540-47987-2_41.

Sutter, H. (2005) 'A Fundamental Turn Toward Concurrency In Software: Your Free Lunch Will Soon Be Over. What Can You Do About It', *Dr. Dobb's Journal*, 30(3), pp. 16–22.

Sutton, J. and Austin, Z. (2015) 'Qualitative Research: Data Collection, Analysis, and Management.', *The Canadian journal of hospital pharmacy*. Canadian Society Of Hospital Pharmacists, 68(3), pp. 226–31. doi: 10.4212/cjhp.v68i3.1456.

Suzuki, H. and Kato, H. (1993) 'AlgoBlock: a tangible programming language, a tool for collaborative learning', *Proceedings of 4th European Logo Conference*, (June 2016), pp. 297–303.

Suzuki, H. and Kato, H. (1995) 'Interaction-level support for collaborative learning: AlgoBlock—an open programming language', *The first international conference on computer support for collaborative learning*, pp. 349–355. doi: 10.3115/222020.222828.

Swain, C. (2006) 'Preservice Teachers Self-Assessment Using Technology : Determining What is Worthwhile and Looking for Changes in Daily Teaching and Learning Practices', *Journal of Technology and Teacher Education*, 14(1), pp. 29–59. doi: 10.1016/j.tate.2009.06.014.

Swain, J. (1997) 'Simulation Software Survey', *INFORMS Today*, 42(5), pp. 38–46.

Sylla, C. *et al.* (2012) 'TUIs vs. GUIs: Comparing the learning potential with preschoolers', *Personal and Ubiquitous Computing*, 16(4), pp. 421–432. doi: 10.1007/s00779-011-0407-z.

Systems Cisco (2010) 'Cisco Packet Tracer - Networking Academy', *Cisco Press*, 1(2), pp. 1–3. doi: C78-552124-01.

Takahashi, A. *et al.* (2016) 'Design of advanced active and autonomous learning system for computing education - A3 learning system', in *Proceedings of 2015 IEEE International Conference on Teaching, Assessment and Learning for Engineering, TALE 2015*, pp. 77–82. doi: 10.1109/TALE.2015.7386020.

Takama, Y., Ito, T. and Ishikawa, H. (2015) 'NFC-based Tangible User Interface for information curation and its application to analogy game', in *Procedia Computer Science*, pp. 1263–1270. doi: 10.1016/j.procs.2015.08.192.

Tanenbaum, J. and Tomizu, A. (2008) 'Narrative Meaning Creation in Interactive Storytelling', *International Journal of Computational Science*, 2(1), pp. 3–20.

Tang, D. P. and Chen, L. J. (2011) 'A review of the evolution of research on information Technology Acceptance Model', in *2011 International Conference on Business Management and Electronic Information*, pp. 588–591. doi: 10.1109/ICBMEI.2011.5917980.

Tanhua-Piiroinen, E., Pystynen, J. and Raisamo, R. (2010) ‘Haptic applications as physics teaching tools’, in *HAVE 2010 - 2010 IEEE International Symposium on Haptic Audio-Visual Environments and Games, Proceedings*, pp. 117–122. doi: 10.1109/HAVE.2010.5623971.

Tarhini, A. *et al.* (2017) ‘Examining the moderating effect of individual-level cultural values on users’ acceptance of E-learning in developing countries: a structural equation modeling of an extended technology acceptance model’, *Interactive Learning Environments*. Routledge, 25(3), pp. 306–328. doi: 10.1080/10494820.2015.1122635.

Tateosian, L. *et al.* (2010) ‘TanGeoMS: Tangible geospatial modeling system’, *IEEE Transactions on Visualization and Computer Graphics*, 16(6), pp. 1605–1612. doi: 10.1109/TVCG.2010.202.

Taylor, D. (no date) *Multitouch Table Technology and Design*. Available at: https://danoataylor.wordpress.com/multitouch-table-project/ (Accessed: 23 February 2017).

Taylor, S. and Todd, P. A. (1995) ‘Understanding information technology usage: A test of competing models’, *Information Systems Research*, 6(2), pp. 144–176. doi: 10.1287/isre.6.2.144.

Teo, T. *et al.* (2008) ‘Beliefs about teaching and uses of technology among pre-service teachers’, *Asia-Pacific Journal of Teacher Education*, 36(2), pp. 163–174. doi: 10.1080/13598660801971641.

Teo, T. (2009) ‘Modelling technology acceptance in education: A study of pre-service teachers’, *Computers and Education*. Elsevier Ltd, 52(2), pp. 302–312. doi: 10.1016/j.compedu.2008.08.006.

Teo, T. (2011) *Technology Acceptance in Education*. Rotterdam, The Netherlands : Sense Publishers. doi: 978-94-6091-486-7.

Teo, T. (2016) ‘Modelling Facebook usage among university students in Thailand: the role of emotional attachment in an extended technology acceptance model’, *Interactive Learning Environments*. Taylor & Francis, 24(4), pp. 745–757. doi: 10.1080/10494820.2014.917110.

Teo, T., Ursavaş, Ö. F. and Bahçekapili, E. (2012) ‘An assessment of pre-service teachers’ technology acceptance in Turkey: A structural equation modeling approach’, *Asia-Pacific Education Researcher*, 21, pp. 191–202.

Terenzini, P. T. *et al.* (2001) ‘Collaborative Learning vs . Lecture / Discussion : Students ’ Reported Learning Gains *’, *Journal of Engineering Education*. Wiley-Blackwell, 90(634066), pp. 123–130. doi: 10.1002/j.2168-9830.2001.tb00579.x.

Terrenghi, L. *et al.* (2005) ‘A cube to learn: a tangible user interface for the design of a learning appliance’, *Personal and Ubiquitous Computing*, 10(2–3), pp. 153–158. doi: 10.1007/s00779-005-0025-8.

Terrenghi, L. *et al.* (2006) ‘Information visualization and interaction techniques for collaboration across multiple displays’, *CHI ’06 extended abstracts on Human factors in computing systems - CHI ’06*, p. 1643. doi: 10.1145/1125451.1125752.

Tetteroo, D., Soute, I. and Markopoulos, P. (2013) ‘Five key challenges in end-user development for tangible and embodied interaction’, *Proceedings of the 15th ACM on International conference on multimodal interaction - ICMI ’13*, pp. 247–254. doi: 10.1145/2522848.2522887.

Theano Development Team (2016) ‘Theano: A Python framework for fast computation of mathematical expressions’, *arXiv e-prints*, abs/1605.0.

Thong, J., Hong, W. and Tam, K. (2002) ‘Understanding user acceptance of digital libraries: what are the roles of interface characteristics, organizational context, and individual differences?’, *International Journal of Human-Computer Studies*, 57(3), pp. 215–242. doi: 10.1006/ijhc.1024.

Thornton, C. J. and du Boulay, B. (1992) *Artificial Intelligence Through Search*. Dordrecht: Springer Netherlands. doi: 10.1007/978-94-011-2836-0.

Tight, M. (2014) ‘Theory development and application in higher education research: The case of threshold concepts’, in Huisman, J. and Malcolm Tight (eds) *Theory and Method in Higher Education Research II*, pp. 249–267. doi: 10.1108/S1479-3628(2014)0000010018.

Tindell, D. R. and Bohlander, R. W. (2012) ‘The Use and Abuse of Cell Phones and

Text Messaging in the Classroom: A Survey of College Students', *College Teaching*. Taylor & Francis Group , 60(1), pp. 1–9. doi: 10.1080/87567555.2011.604802.

Touretzky, D. S. (2014) 'Teaching Kodu with physical manipulatives', *ACM Inroads*. ACM, 5(4), pp. 44–51. doi: 10.1145/2684721.2684732.

True, J. A. and Bryman, A. (1990) 'Quantity and Quality in Social Research.', *Contemporary Sociology*. doi: 10.2307/2072662.

Trümper, J., Bohnet, J. and Döllner, J. (2010) 'Understanding complex multithreaded software systems by using trace visualization', in *Proceedings of the 5th international symposium on Software visualization*, pp. 133–142. doi: 10.1145/1879211.1879232.

Truong, H. M. (2016) 'Integrating learning styles and adaptive e-learning system: Current developments, problems and opportunities', *Computers in Human Behavior*, 55, pp. 1185–1193. doi: 10.1016/j.chb.2015.02.014.

Tseng, T., Bryant, C. and Blikstein, P. (2011) 'Mechanix: An interactive display for exploring engineering design through a tangible interface', *Proceedings of the international conference on Tangible, embedded, and embodied interaction (TEI '11)*, pp. 265–266. doi: 10.1145/1935701.1935757.

Tufford, L. and Newman, P. (2012) 'Bracketing in Qualitative Research', *Qualitative Social Work: Research and Practice*. SAGE PublicationsSage UK: London, England, 11(1), pp. 80–96. doi: 10.1177/1473325010368316.

Turchi, T. and Malizia, A. (2016) 'A Human-Centred Tangible approach to learning Computational Thinking', *ICST Transactions on Ambient Systems*, 3(9), p. 151641. doi: 10.4108/eai.23-8-2016.151641.

Turner, K. J. and Robin, I. A. (2001) 'An interactive visual protocol simulator', *Computer Standards and Interfaces*, 23(4), pp. 279–310. doi: 10.1016/S0920-5489(01)00081-2.

Turner, M. *et al.* (2010) 'Does the technology acceptance model predict actual use? A systematic literature review', *Information and Software Technology*, pp. 463–479. doi: 10.1016/j.infsof.2009.11.005.

Uke, N. J. and Thool, R. C. (2011) 'Playfully teaching artificial intelligence by implementing games to undergraduates', in *Proceedings of the International Conference & Workshop on Emerging Trends in Technology - ICWET '11*. New York, New York, USA: ACM Press, p. 1377. doi: 10.1145/1980022.1980408.

Ukil, M. and Sorathia, K. (2014) 'Re-defining learning experience for kids', in *IEEE TechSym 2014 - 2014 IEEE Students' Technology Symposium*, pp. 218–223. doi: 10.1109/TechSym.2014.6808050.

Ullmer and Anders, B. (2002) 'Tangible interfaces for manipulating aggregates of digital information'. Massachusetts Institute of Technology.

Ullmer, B. and Ishii, H. (1997) 'The metaDESK: models and prototypes for tangible user interfaces', *Proceedings of the 10th annual ACM symposium on User interface software and technology - UIST '97*, pp. 223–232. doi: 10.1145/263407.263551.

Ullmer, B. and Ishii, H. (2001) 'Emerging frameworks for tangible user interfaces', *IBM Systems Journal*, 39(3.4), pp. 915–931. doi: 10.1147/sj.393.0915.

Ullmer, B., Ishii, H. and Glas, D. (1998) 'mediaBlocks: physical containers, transports, and controls for online media', *Proc. SIGGRAPH´98*, 32, pp. 379–386. doi: 10.1145/280814.280940.

Ullmer, B., Ishii, H. and Jacob, R. J. K. (2003) 'Tangible Query Interfaces: Physically Constrained Tokens for Manipulating Database Queries', *Science*, 03(c), pp. 279–286. doi: 10.1.1.13.1780.

Ullmer, B., Ishii, H. and Jacob, R. J. K. (2005) 'Token+constraint systems for tangible interaction with digital information', *ACM Transactions on Computer-Human Interaction*, 12(1), pp. 81–118. doi: 10.1145/1057237.1057242.

Underkoffler, J. and Ishii, H. (1998) 'Illuminating Light : An Optical Design Tool with a Luminous-Tangible Interface', *Proceedings of the ACM Conference on Human Factors in Computing Systems*, (April), pp. 542–549. doi: 10.1145/274644.274717.

Underkoffler, J. and Ishii, H. (1999) 'Urp: A luminous-tangible workbench for urban planning and design', in *Proceedings of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*, pp. 386–393. doi: 10.1145/302979.303114.

Urval, R. P. *et al.* (2014) 'Assessment of learning styles of undergraduate medical students using the VARK questionnaire and the influence of sex and academic performance', *AJP: Advances in Physiology Education*. American Physiological Society Bethesda, MD, 38(3), pp. 216–220. doi: 10.1152/advan.00024.2014.

Uttal, D. H., Scudder, K. V. and DeLoache, J. S. (1997) 'Manipulatives as symbols: A new perspective on the use of concrete objects to teach mathematics', *Journal of Applied Developmental Psychology*, 18(1), pp. 37–54. doi: 10.1016/S0193-3973(97)90013-7.

Vallacher, R. and Kaufman, J. (1996) 'Dynamics of action identification: Volatility and structure in the mental representation of behavior', in P.M. Gollwitzer & J. A. Bargh (ed.) *The psychology of action: Linking cognition and motivation to behavior*. New York: Guilford., pp. 260–282.

Vallacher, R. R. and Wegner, D. M. (1987) 'What do people think they're doing? Action identification and human behavior.', *Psychological Review*, 94(1), pp. 3–15. doi: 10.1037/0033-295X.94.1.3.

De Vaus, D. (2013) *Surveys in social research*. 6th edn. Allen & Unwin.

Venkatesh, V. (1999) 'Creation of Favorable User Perceptions: Exploring the Role of Intrinsic Motivation', *MIS Quarterly*, 23(2), p. 239. doi: 10.2307/249753.

Venkatesh, V. (2000) 'Determinants of Perceived Ease of Use: Integrating Control, Intrinsic Motivation, and Emotion into the Technology Acceptance Model', *Information Systems Research*. INFORMS, 11(4), pp. 342–365. doi: 10.1287/isre.11.4.342.11872.

Venkatesh, V. *et al.* (2003) 'User Acceptance of Information Technology: Toward a unified view', *MIS Quarterly*, 27(3), pp. 425–478. doi: 10.1017/CBO9781107415324.004.

Venkatesh, V. and Bala, H. (2008) 'Technology acceptance model 3 and a research agenda on interventions', *Decision Sciences*, 39(2), pp. 273–315. doi: 10.1111/j.1540-5915.2008.00192.x.

Venkatesh, V. and Davis, Fred D (2000) 'Theoretical extension of the Technology Acceptance Model: Four longitudinal field studies', *Management science*. INFORMS, 46(2), pp. 186–204. doi: 10.2307/2634758.

Venkatesh, V. and Davis, Fred D. (2000) ‘Theoretical extension of the Technology Acceptance Model: Four longitudinal field studies’, *Management science*. INFORMS, 46(2), pp. 186–204. doi: 10.2307/2634758.

Venkatesh, V., Morris, M. and Ackerman, P. (2000) ‘A Longitudinal Field Investigation of Gender Differences in Individual Technology Adoption Decision-Making Processes.’, *Organizational behavior and human decision processes*, 83(1), pp. 33–60. doi: 10.1006/obhd.2000.2896.

Vidarte, J. D. T. *et al.* (2010) ‘A Tangible interface for learning recursion and functional programming’, in *Proceedings - 2010 International Symposium on Ubiquitous Virtual Reality, ISUVR 2010*. IEEE, pp. 32–35. doi: 10.1109/ISUVR.2010.18.

Vinot, J.-L. *et al.* (2014) ‘Tangible augmented reality for air traffic control’, *interactions*. ACM, 21(4), pp. 54–57. doi: 10.1145/2627598.

Virnes, M., Sutinen, E. and Kärnä-Lin, E. (2008) ‘How children’s individual needs challenge the design of educational robotics’, in *Interaction Design and Children*, pp. 274–281. doi: 10.1145/1463689.1463766.

Vroom, V. H. (1964) *Work and motivation*, *Classic readings in organizational behavior*.

Vu, X.-T., Abel, M.-H. and Morizet-Mahoudeaux, P. (2015) ‘A user-centered approach for integrating social data into groups of interest’, *Data & Knowledge Engineering*, 96–97, pp. 43–56. doi: 10.1016/j.datak.2015.04.004.

Vygotsky, L. S. (1978) *Mind in society: The development of higher psychological processes*, *Mind in Society The Development of Higher Psychological Processes*. doi: 10.1007/978-3-540-92784-6.

Waard, I. De *et al.* (2011) ‘Exploring the MOOC format as a pedagogical approach for mLearning’, *mLearn 2011*, pp. 138–148.

Wade, V., Wade, V. and Lyng, M. (2000) ‘An automated Evaluation Service for Educational Courseware’, *WebNet World Conference on the WWW and Internet*, 2000(1), pp. 569–574.

Wagner, S. M., Nusbaum, H. and Goldin-Meadow, S. (2004) ‘Probing the mental representation of gesture: Is handwaving spatial?’, *Journal of Memory and Language*, 50(4), pp. 395–407. doi: 10.1016/j.jml.2004.01.002.

Wang, D. *et al.* (2015) ‘A TUI-based Programming Tool for Children’, in *Proceedings of the 2015 ACM Conference on Innovation and Technology in Computer Science Education - ITiCSE ’15*, pp. 219–224. doi: 10.1145/2729094.2742630.

Wang, D. *et al.* (2016) ‘A Tangible Embedded Programming System to Convey Event-Handling Concept’, *Proceedings of the TEI ’16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI ’16*, pp. 133–140. doi: 10.1145/2839462.2839491.

Wang, D., Wang, T. and Liu, Z. (2014) ‘A tangible programming tool for children to cultivate computational thinking’, *The Scientific World Journal*, 2014. doi: 10.1155/2014/428080.

Wang, D., Zhang, Y. and Chen, S. (2013) ‘E-block: A tangible programming tool with graphical blocks’, *Mathematical Problems in Engineering*, 2013. doi: 10.1155/2013/598547.

Wang, P. A. (2012) ‘Information security knowledge and behavior: An adapted model of technology acceptance’, *International Conforence on Education Technology and Computer*, 2, pp. 364–367. doi: 10.1109/ICETC.2010.5529366.

Wang, S. J., Moriarty, P. and Wu, S.-Z. (2015) ‘Tangible Interaction Design: Preparing Future Designers for the Needs of Industrial Innovation’, *Procedia Technology*, 20, pp. 162–169. doi: 10.1016/j.protcy.2015.07.027.

Waranusast, R., Bang-ngoen, A. and Thipakorn, J. (2013) ‘Interactive tangible user interface for music learning’, *2013 28th International Conference on Image and Vision Computing New Zealand (IVCNZ 2013)*, pp. 400–405. doi: 10.1109/IVCNZ.2013.6727048.

Warshaw, P. R. (1980) ‘A New Model for Predicting Behavioral Intentions: An Alternative to Fishbein’, *J. Mark. Res.*, 17(2), pp. 153–172. doi: 10.2307/3150927.

Weghorst, S. (2003) ‘Augmented Tangible Molecular Models’, in *IWSM’03-’04: The Fourth International Workshop on Spatial Media and the Sixth International Conference on Humans and Computers.*

Weibel, N. *et al.* (2012) 'Digital pen and paper practices in observational research', in *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. New York, New York, USA: ACM Press, p. 1331. doi: 10.1145/2207676.2208590.

Weinberg, J. B. and Yu, X. (2003) 'Robotics in education: Low-cost platforms for teaching integrated systems', *IEEE Robotics and Automation Magazine*, June, pp. 4–6. doi: 10.1109/MRA.2003.1213610.

Weiser, M. (1993) 'Ubiquitous computing', *Computer*, 26(10), pp. 71–72. doi: 10.1109/2.237456.

Weiss, B., Gridling, G. and Proske, M. (2005) 'A Case Study In Efficient Microcontroller Education', *ACM SIGBED Review*. ACM, 2(4), pp. 40–47.

Wellner, P. (1993) 'Interacting with paper on the DigitalDesk', *Communications of the ACM*, 36(7), pp. 87–96. doi: 10.1145/159544.159630.

Weltman, D. (2007) *A comparison of traditional and active learning methods : an empirical investigation utilizing a linear mixed model*. ProQuest Dissertations and Theses (Electronic resource collection) University of Texas at Arlington. College of Business Administration. Information Systems and Operations Management, Ph. D.

Wensveen, S. A. G., Djajadiningrat, J. P. and Overbeeke, C. J. (2004) 'Interaction frogger: a design framework to couple action and function through feedback and feedforward', *DIS '04 Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques*, pp. 177–184. doi: 10.1145/1013115.1013140.

Westeyn, T. L. *et al.* (2008) 'Designing Toys with Automatic Play Characterization for Supporting the Assessment of a Child's Development', *Proc. Int. Conf. on Interaction Design and Children*, pp. 89–92. doi: 10.1145/1463689.1463726.

Wickens, C. D. and Hollands, J. G. (2000) *Engineering Psychology and Human Performance*, *Engineering psychology and human performance*. doi: 10.1146/annurev.ps.27.020176.001513.

Wiemer-Hastings, K. and Xu, X. (2005) 'Content Differences for Abstract and Concrete

Concepts', *Cognitive Science*. Lawrence Erlbaum Associates, Inc., 29(5), pp. 719–736. doi: 10.1207/s15516709cog0000_33.

Wiethoff, A. *et al.* (2012) 'Sketch - a - TUI : Low Cost Prototyping of Tangible Interactions U sing Cardboard and Conductive Ink', *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, 1(212), pp. 309–312. doi: 10.1145/2148131.2148196.

Wiethoff, A. *et al.* (2013) 'Paperbox – A toolkit for exploring tangible interaction on interactive surfaces', *Proceedings of the 9th ACM Conference on Creativity & Cognition - C&C '13*. New York, New York, USA: ACM Press, pp. 64–73. doi: 10.1145/2466627.2466635.

Wiley, D. A. (2002) *The Instructional Use of Learning Objects*. 1st edn. Edited by D. A. Wiley. Agency for Instructional Technology and Association for Educational Communications & Technology.

Williams, B., Onsman, A. and Brown, T. (1996) 'Exploratory factor analysis: A five-step guide for novices', *Journal of Emergency Primary Health Care*, 19(May), pp. 42–50. doi: 10.1080/09585190701763982.

Williams, C. (2002) 'Learning On-line: A review of recent literature in a rapidly expanding field', *Journal of Further and Higher Education*. Taylor & Francis Group , 26(3), pp. 263–272. doi: 10.1080/03098770220149620.

Williams, D. L., Boone, R. and Kingsley, K. V (2004) 'Teacher beliefs about educational software: A Delphi study', *Journal of Research on Technology in Education*, 36, pp. 213–229. doi: 10.1080/15391523.2004.10782413.

Wilson, B. G. and Myers, K. M. (2000) 'Situated Cognition in Theoretical and Practical Context', in *Theoretical Foundations of Learning Environments*, pp. 57–88. doi: citeulike-article-id:1013375.

Wilson Van Voorhis, C. R. and Morgan, B. L. (2007) 'Understanding Power and Rules of Thumb for Determining Sample Sizes', *Tutorials in Quantitative Methods for Psychology*, 3(2), pp. 43–50. doi: 10.20982/tqmp.03.2.p043.

Wing, J. M. (2006) 'Computational thinking', *Communications of the ACM*, 49(3), p.

33. doi: 10.1145/1118178.1118215.

Winne, P. H. and Nesbit, J. C. (2010) 'The Psychology of Academic Achievement', *Annual Review of Psychology*, 61(1), pp. 653–678. doi: 10.1146/annurev.psych.093008.100348.

Wirtz, B. W. and Göttel, V. (2016) 'Technology Acceptance in Social Media : Review , Synthesis and Directions for Future Empirical Research', *Journal of Electronic Commerce Research*, 17(2), pp. 97–115.

Wixom, B. H. and Todd, P. A. (2005) 'A theoretical integration of user satisfaction and technology acceptance', *Information Systems Research*, 16(1), pp. 85–102. doi: 10.1287/isre.1050.0042.

Wolber, D. and Abelson, H. (2011) *App Inventor: Create your Own Android Apps*. Edited by S. Ellen and L. Liz. Sebastopol, CA : O'Reilly.

Wolffe, G. and Trefftz, C. (2009) 'Teaching Parallel Computing: New Possibilities', *J. Comput. Sci. Coll.*, 25(1), pp. 21–28.

Wollowski, M. *et al.* (2016) 'A Survey of Current Practice and Teaching of AI', *Proceedings of the 30th Conference on Artificial Intelligence (AAAI 2016)*. AAAI Press, pp. 4119–4124.

Wong, D., Zink, R. and Koenig, S. (2010) 'Teaching artificial intelligence and robotics via games', in *Proceedings of the National Conference on Artificial Intelligence*, pp. 1917–1918.

Wong, K. T. *et al.* (2013) 'Understanding student teachers ' behavioural intention to use technology: Technology Acceptance Model (TAM) validation and testing', *International Journal of Instruction*, 6(1), pp. 89–105.

Wood, D., Bruner, J. S. and Ross, G. (1976) 'The role of tutoring in problem-solving', *Journal of Child Psychology and Psychiatry*, 17(September 1974), pp. 89–100. doi: 10.1111/j.1469-7610.1976.tb00381.x.

Wu, A. *et al.* (2011) 'A framework interweaving tangible objects, surfaces and spaces', in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, pp. 148–157. doi: 10.1007/978-3-

642-21605-3_17.

Wu, B. and Chen, X. (2017) 'Continuance intention to use MOOCs: Integrating the technology acceptance model (TAM) and task technology fit (TTF) model', *Computers in Human Behavior*, 67, pp. 221–232. doi: 10.1016/j.chb.2016.10.028.

Wu, B. and Zhang, C. (2014) 'Empirical study on continuance intentions towards E-Learning 2.0 systems', *Behaviour and Information Technology*, 33(10), pp. 1027–1038. doi: 10.1080/0144929X.2014.934291.

Wu, C.-S. *et al.* (2011) 'User acceptance of wireless technology in organizations: A comparison of alternative models', *Computer Standards & Interfaces*, 33(1), pp. 50–58. doi: 10.1016/j.csi.2010.03.002.

Wu, D. C. (2014) 'Learning styles and satisfaction in distance education', *Turkish Online Journal of Distance Education*, 15(4), pp. 112–129.

Wu, K. *et al.* (2011) 'A meta-analysis of the impact of trust on technology acceptance model: Investigation of moderating influence of subject and context type', *International Journal of Information Management*, 31(6), pp. 572–581. doi: 10.1016/j.ijinfomgt.2011.03.004.

Wulf, G., Shea, C. and Lewthwaite, R. (2010) 'Motor skill learning and performance: a review of influential factors', *Medical Education*, 44(1), pp. 75–84. doi: 10.1111/j.1365-2923.2009.03421.x.

Wyeth, P. and Purchase, H. C. (2002) 'Tangible Programming Elements for Young Children', *CHI '02 extended abstracts on Human factors in computing systems - CHI '02*, pp. 774–775. doi: 10.1145/506443.506591.

Xinogalos, S. (2015) 'Object-Oriented Design and Programming : An Investigation of Novices ' Conceptions on Objects and Classes', *ACM Transactions on Computing Education*, 15(3), pp. 13:1-13:21. doi: 10.1145/2700519.

Xue, Y. . *et al.* (2014) 'Understanding healthcare professionals' resistance of telemedicine: An empirical study in Ethiopia', *Proceedings - Pacific Asia Conference on Information Systems, PACIS 2014*.

Yan, L. and Lu (2009) 'Teaching Object-Oriented Programming with Games', in *2009*

Sixth International Conference on Information Technology: New Generations. IEEE, pp. 969–974. doi: 10.1109/ITNG.2009.13.

Yang, S. C. and Lin, C. H. (2011) ‘Factors affecting the intention to use Facebook to support problem-based learning among employees in a Taiwanese manufacturing company’, *African Journal of Business Management*, 5(22), pp. 9014–9022. doi: 10.5897/AJBM11.1191.

Yi, M. Y. and Hwang, Y. (2003) ‘Predicting the use of web-based information systems: Self-efficacy, enjoyment, learning goal orientation, and the technology acceptance model’, *International Journal of Human Computer Studies*, 59(4), pp. 431–449. doi: 10.1016/S1071-5819(03)00114-9.

Yonemoto, S., Yotsumoto, T. and Taniguchi, R. I. (2006) ‘A tangible interface for hands-on learning’, in *Proceedings of the International Conference on Information Visualisation*, pp. 535–538. doi: 10.1109/IV.2006.13.

YouTube (2017) *Artificial Neutral Network*. Available at: https://www.youtube.com/results?search_query=artificial+neural+network (Accessed: 27 September 2017).

Yuan, Y., Yang, X. and Xiao, S. (2007) ‘A framework for tangible user interfaces within projector-based mixed reality’, in *6th IEEE and ACM International Symposium on Mixed and Augmented Reality, ISMAR*. doi: 10.1109/ISMAR.2007.4538868.

Yuen, A. H. K. K. and Ma, W. W. K. K. (2008) ‘Exploring teacher acceptance of e-learning technology’, *Asia-Pacific Journal of Teacher Education*, 36(3), pp. 229–243. doi: 10.1080/13598660802232779.

Zaman, B. *et al.* (2012) ‘Editorial: The evolving field of tangible interaction for children: The challenge of empirical validation’, in *Personal and Ubiquitous Computing*. Springer-Verlag, pp. 367–378. doi: 10.1007/s00779-011-0409-x.

Zappi, P. *et al.* (2009) ‘Hidden Markov Model based gesture recognition on low-cost, low-power Tangible User Interfaces’, *Entertainment Computing*, 1(2), pp. 75–84. doi: 10.1016/j.entcom.2009.09.005.

Zare, H. and Yazdanparast, S. (2013) ‘The causal model of effective factors on intention to use of information technology among payam noor and traditional universities students', *Life Science Journal*, 10(2), pp. 46–50. doi: 10.1007/s13398-014-0173-7.2.

Zhang, J. and Norman, D. A. (1994) 'Representations in distributed cognitive tasks', *Cognitive Science*, 18(1), pp. 87–122. doi: 10.1016/0364-0213(94)90021-3.

Zhang, S., Zhao, J. and Tan, W. (2008) 'Extending TAM for Online Learning Systems: An Intrinsic Motivation Perspective', *Tsinghua Science and Technology*, 13(3), pp. 312–317. doi: 10.1016/S1007-0214(08)70050-6.

Zhou, M. (2016) 'Chinese university students' acceptance of MOOCs: A self-determination perspective', *Computers and Education*, 92–93, pp. 194–203. doi: 10.1016/j.compedu.2015.10.012.

Zuckerman, O. (2015) 'Objects for change: A case study of a tangible user interface for behavior change', *Tei 2015*. New York, New York, USA: ACM Press, pp. 649–654. doi: 10.1145/2677199.2687906.

Zuckerman, O. *et al.* (2016) 'DataSpoon: Overcoming Design Challenges in Tangible and Embedded Assistive Technologies', in *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. New York, New York, USA: ACM Press, pp. 30–37. doi: 10.1145/2839462.2839505.

Zuckerman, O., Arida, S. and Resnick, M. (2005) 'Extending Tangible Interfaces for Education: Digital Montessori-inspired Manipulatives', *CHI'05 Proceedings of the SIGCHI Conference on Human Factors in CS*, pp. 859–868. doi: 10.1145/1054972.1055093.

Zuckerman, O. and Gal-Oz, A. (2013) 'To TUI or not to TUI: Evaluating performance and preference in tangible vs. graphical user interfaces', *International Journal of Human Computer Studies*, 71(7–8), pp. 803–820. doi: 10.1016/j.ijhcs.2013.04.003.

Zuckerman, O. and Resnick, M. (2004) 'Hands-on modeling and simulation of systems', *Proceeding of the 2004 conference on Interaction design and children: building a community*, pp. 157–158. doi: http://doi.acm.org/10.1145/1017833.1017868.

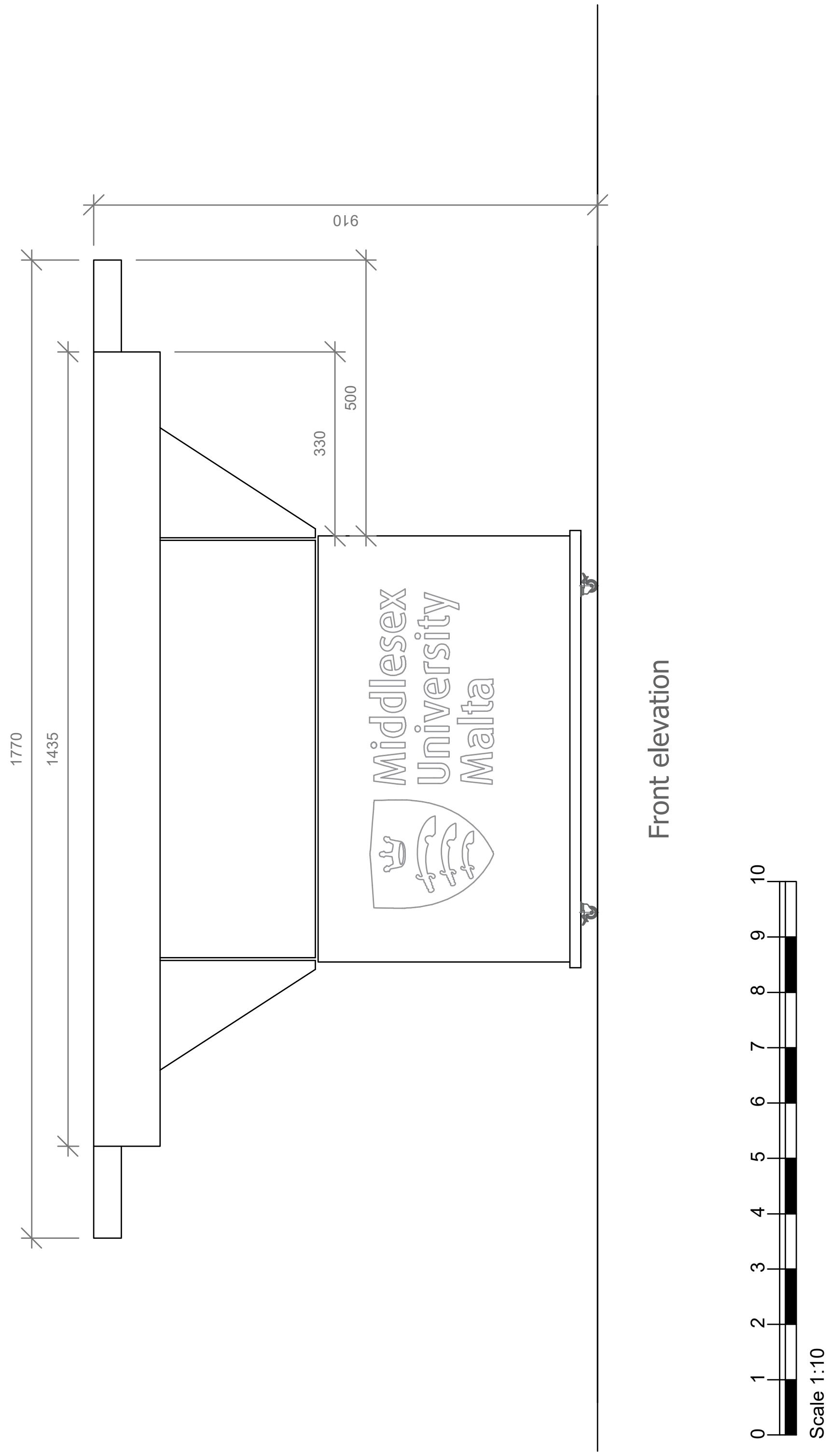
Zufferey, G. *et al.* (2009) 'TinkerSheets: using paper forms to control and visualize tangible simulations', *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, 1, pp. 377–384. doi: 10.1145/1517664.1517740.

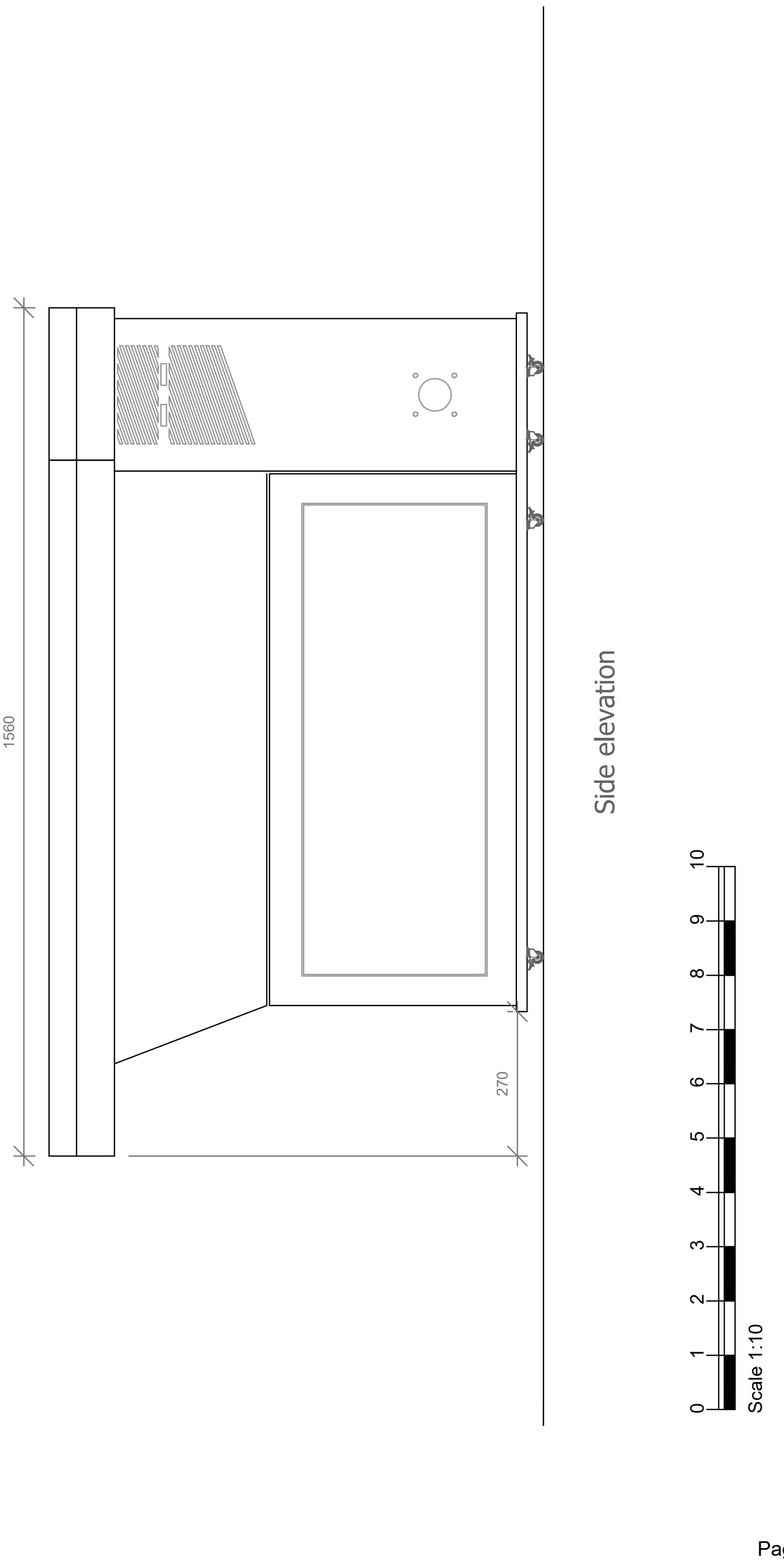
Zyda, M. and Koenig, S. (2008) 'Teaching Artificial Intelligence Playfully', in *Proceedings of the AAAI-08 Education Colloquium*, pp. 90–95.

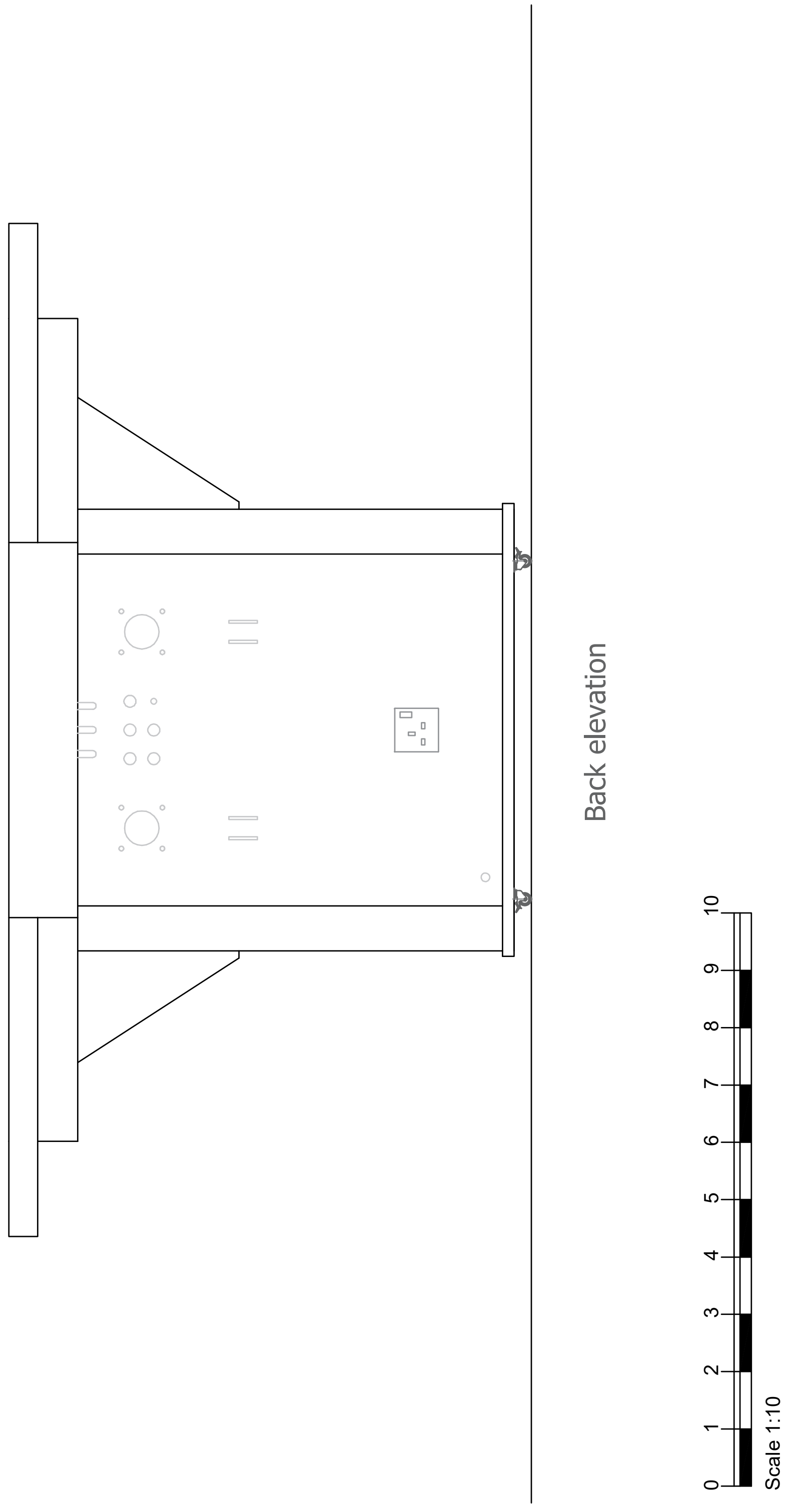
Appendices

Appendix A

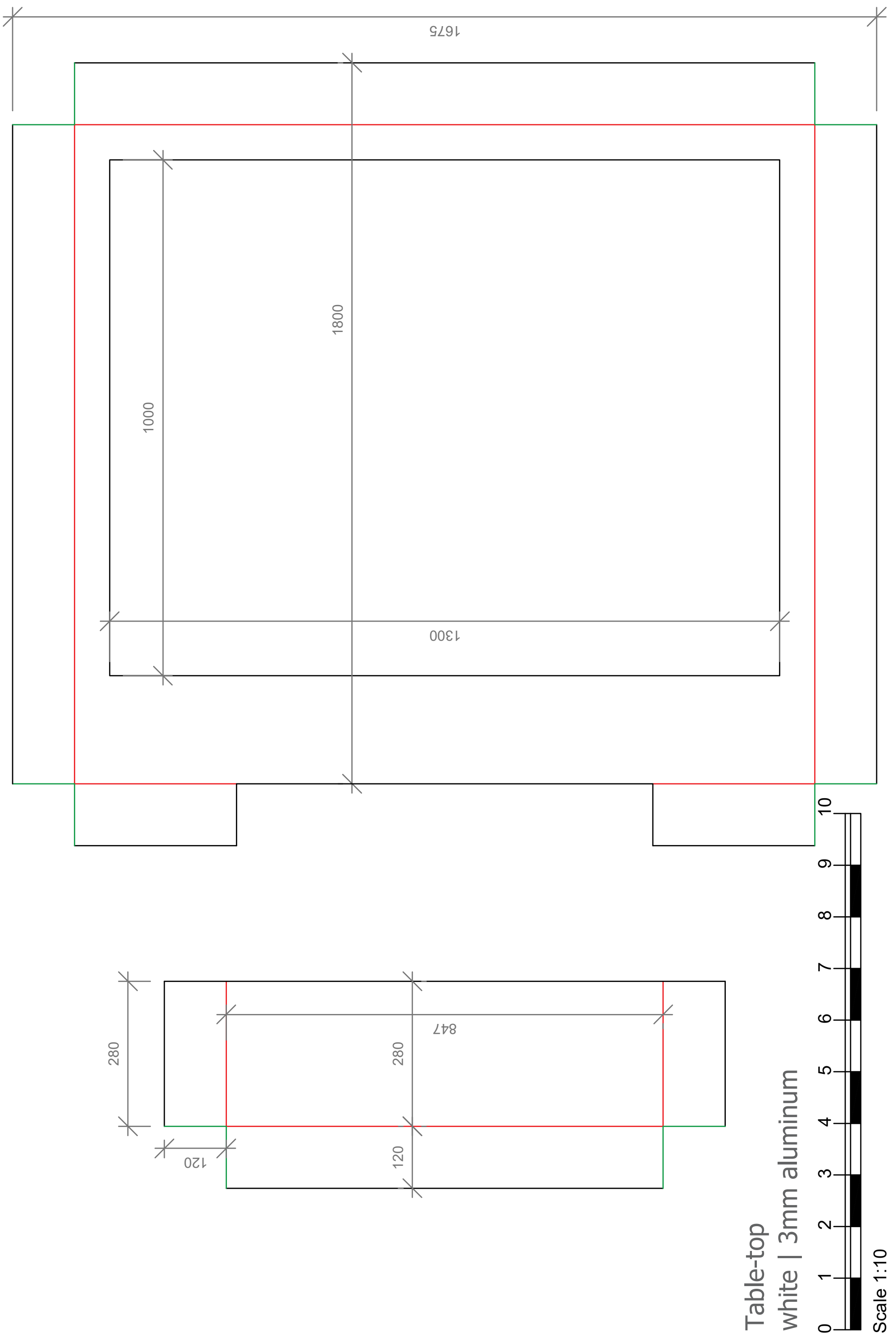
Shop Drawings for Proposed TUI Architecture

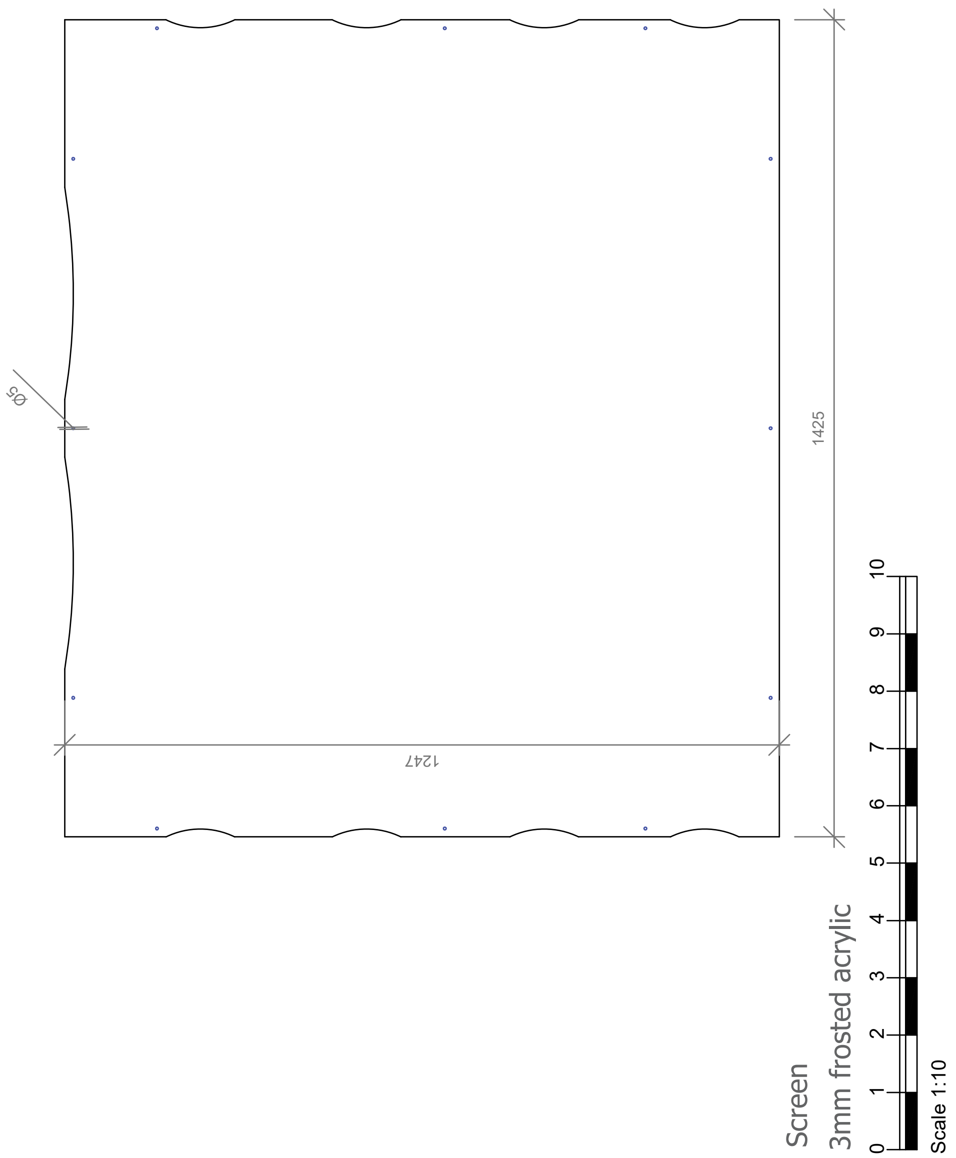

910
1770
1435
500
330
Middlesex University Malta
Front elevation
0 1 2 3 4 5 6 7 8 9 10
Scale 1:10

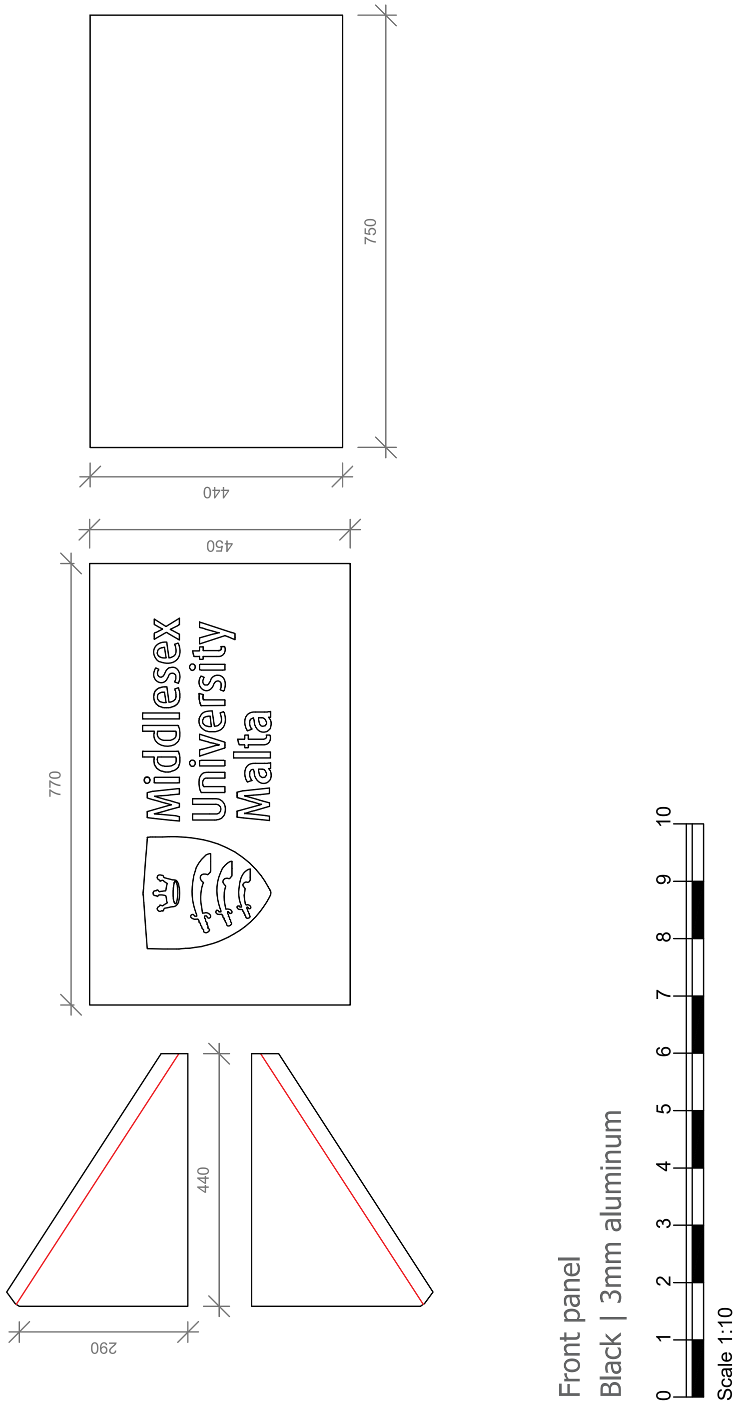

1560
270
Side elevation
0 1 2 3 4 5 6 7 8 9 10
Scale 1:10

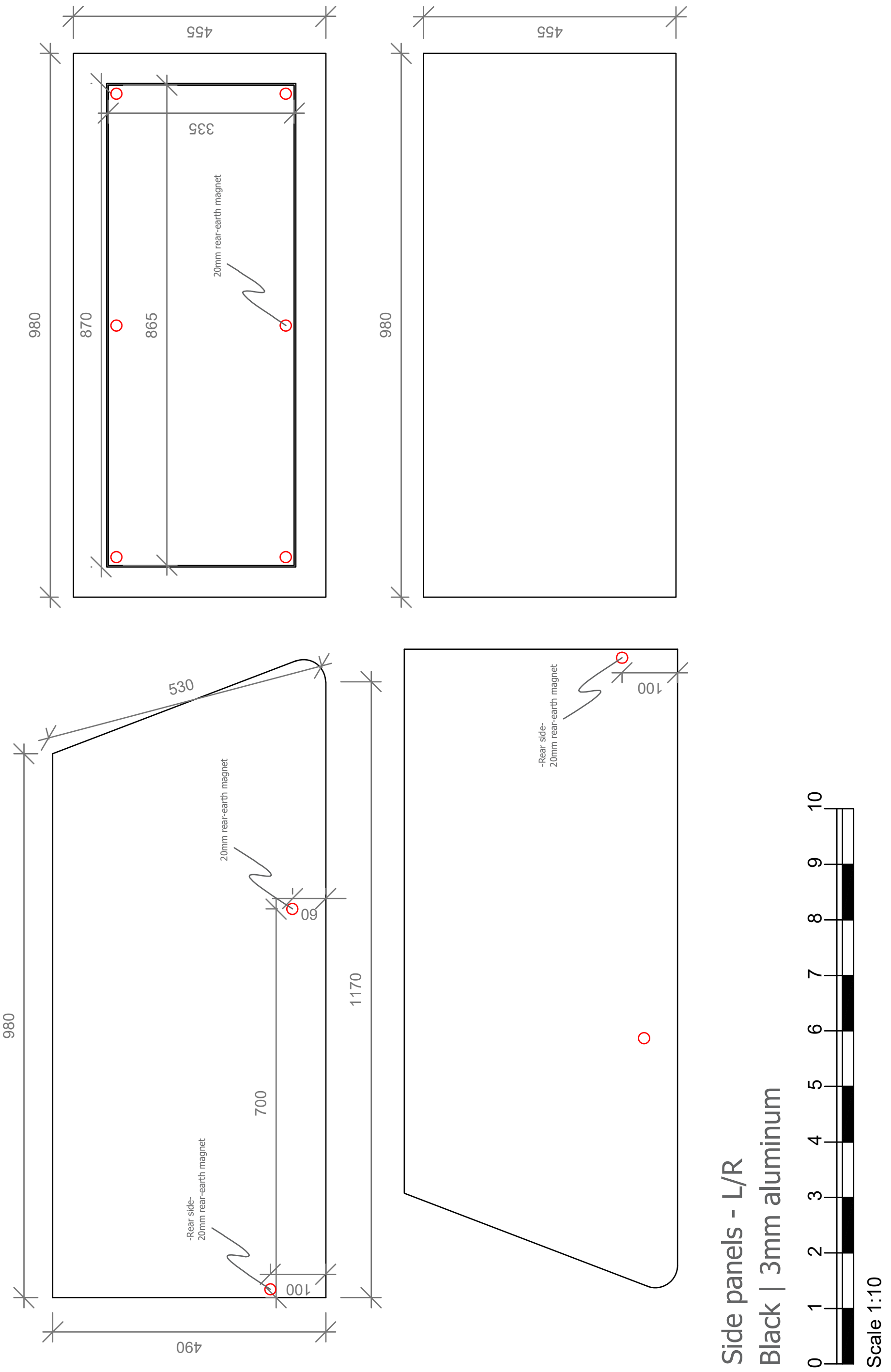


Back elevation

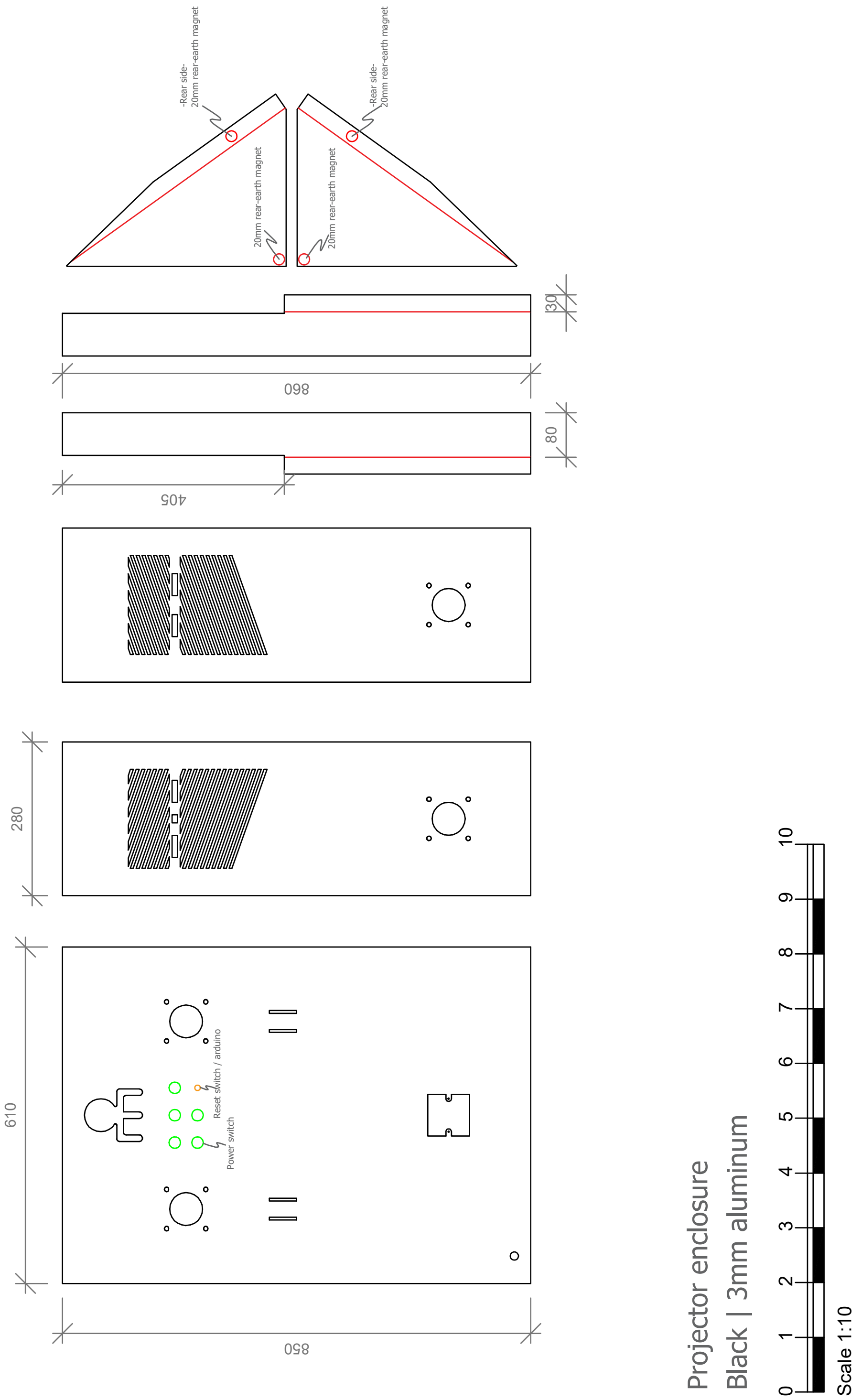

1675
1800
1000
1300
280
847
280
120
120
Table-top
white | 3mm aluminum
0 1 2 3 4 5 6 7 8 9 10
Scale 1:10


1425
1247
Ø5
Screen
3mm frosted acrylic
0 1 2 3 4 5 6 7 8 9 10
Scale 1:10

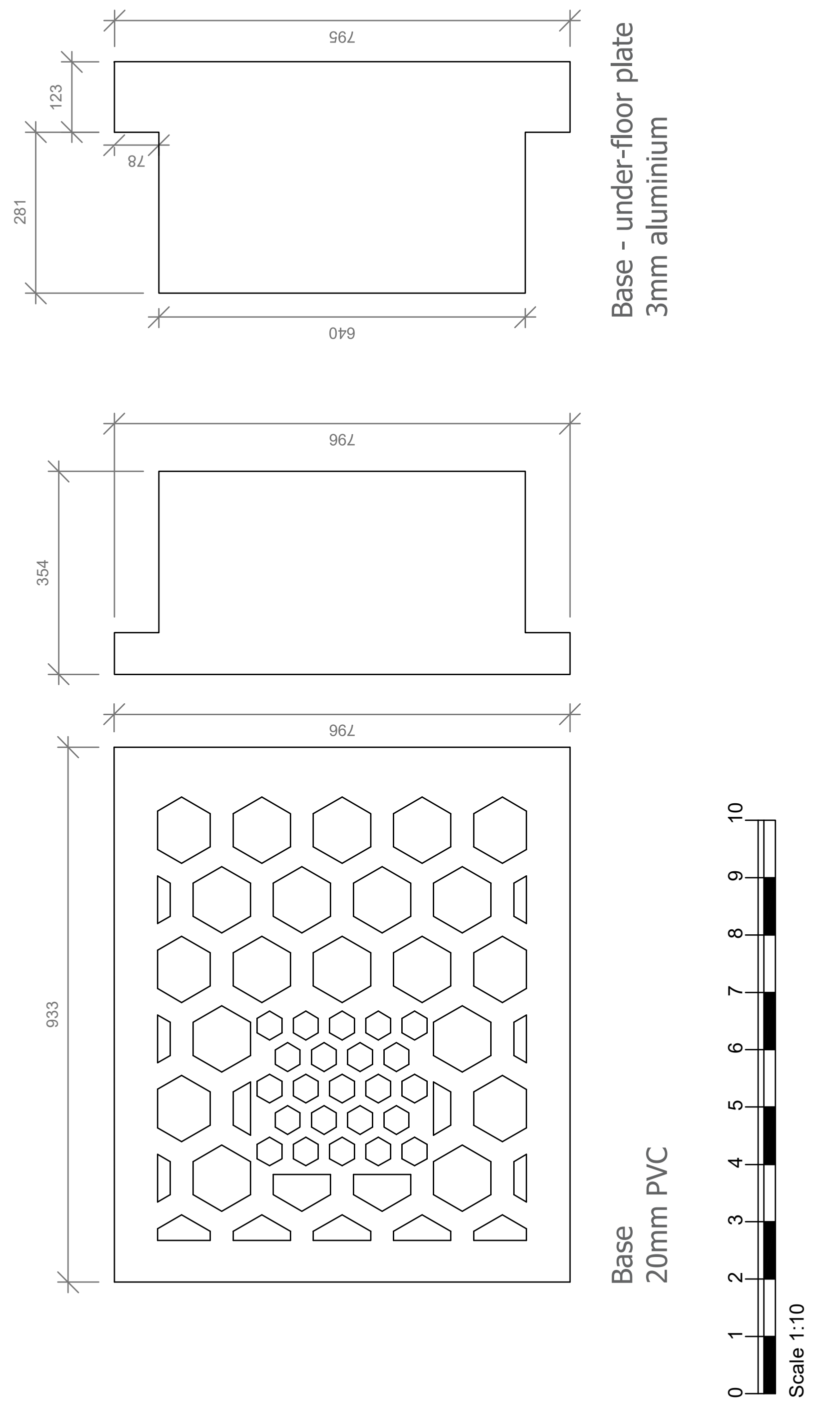

750
440
450
770
Middlesex University Malta
440
290
Front panel
Black | 3mm aluminum
0
1
2
3
4
5
6
7
8
9
10
Scale 1:10

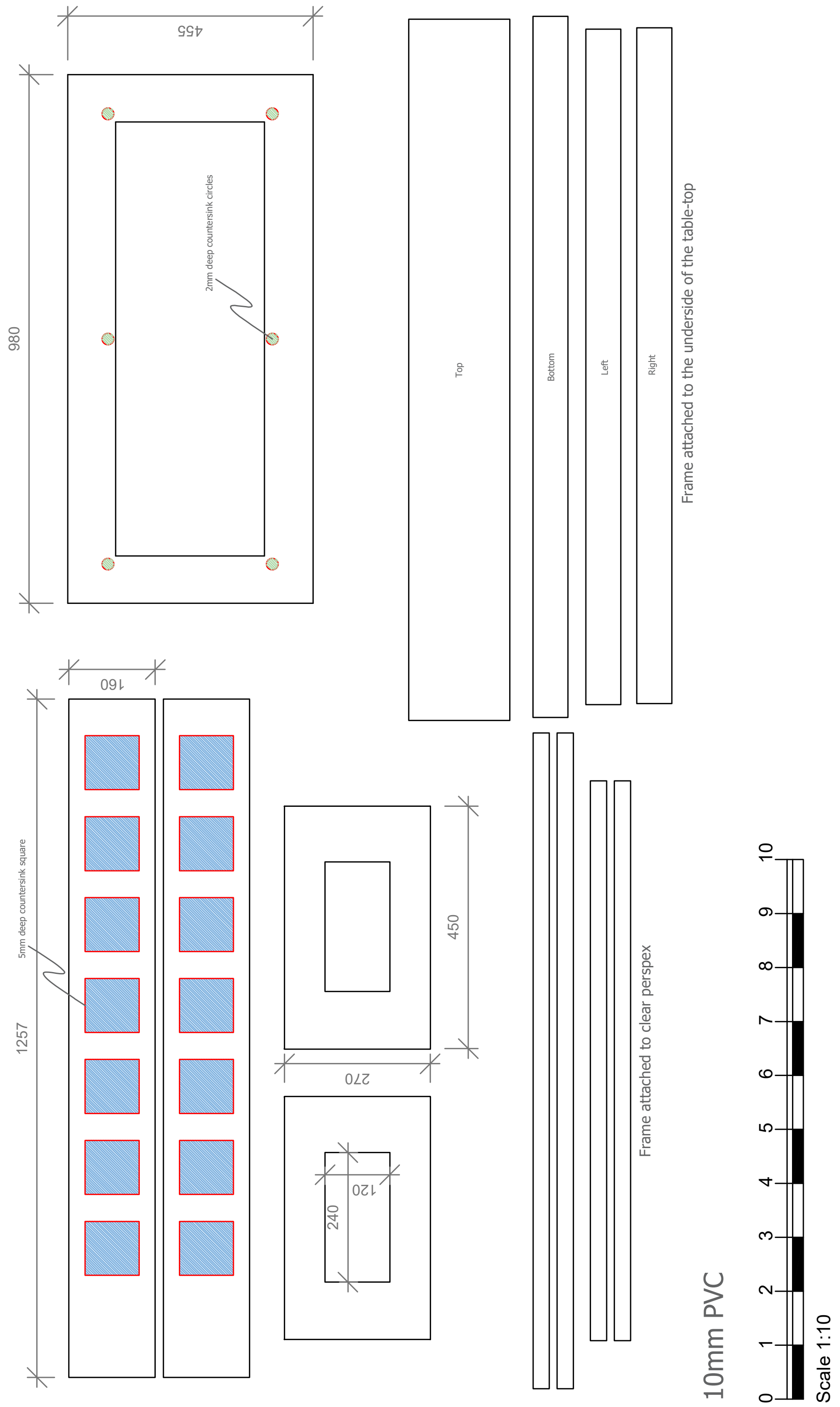


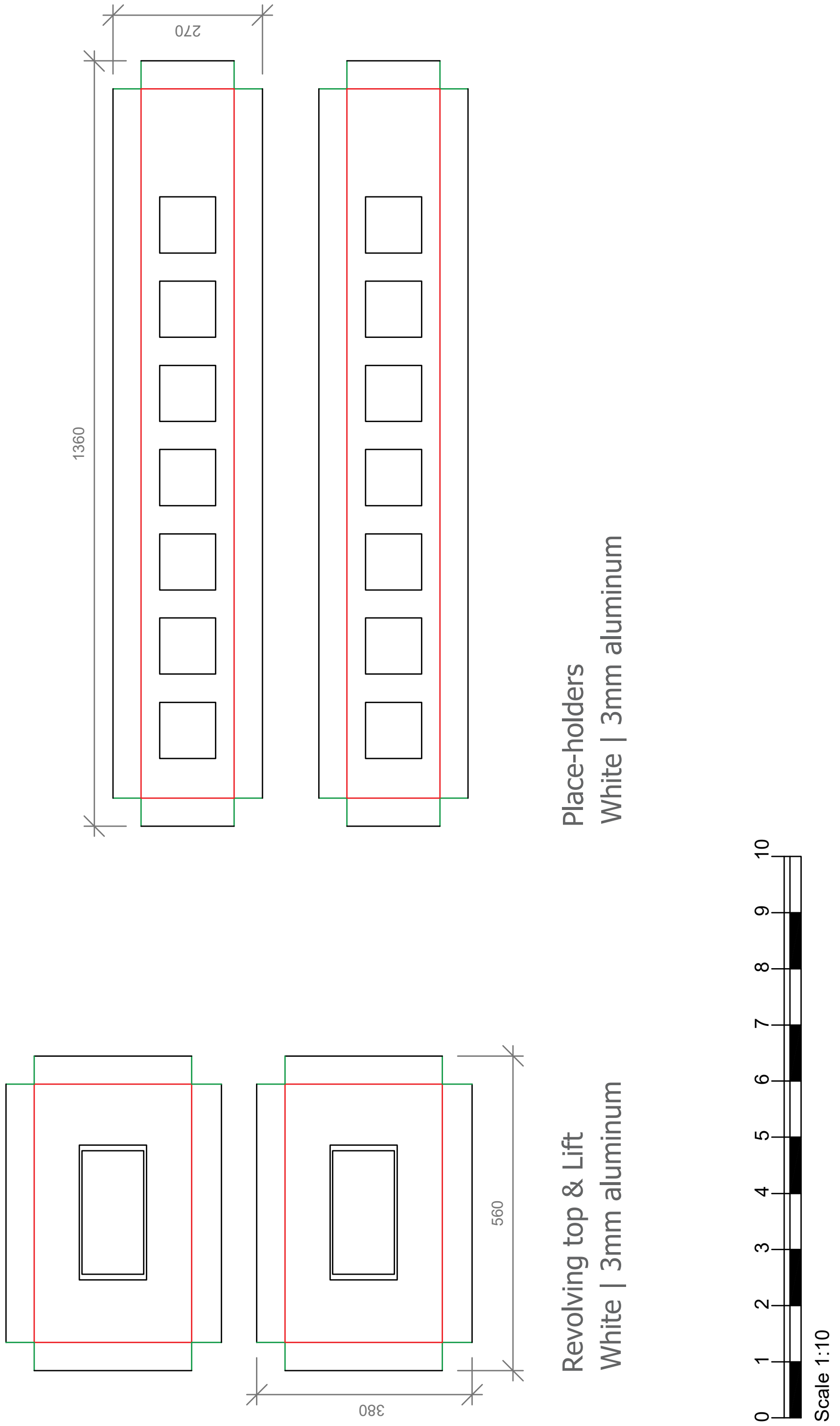
455
455
335
980
870
865
980
20mm rear-earth magnet
530
1170
980
60
700
100
490
100
-Rear side-
20mm rear-earth magnet
Side panels - L/R
Black | 3mm aluminum
Scale 1:10
0
1
2
3
4
5
6
7
8
9
10



-Rear side-
20mm rear-earth magnet
20mm rear-earth magnet
-Rear side-
20mm rear-earth magnet
20mm rear-earth magnet
30
860
80
405
280
610
Reset switch / arduino
Power switch
850
Projector enclosure
Black | 3mm aluminum
0
1
2
3
4
5
6
7
8
9
10
Scale 1:10


Base - under-floor plate
3mm aluminium
795
123
78
281
640
796
354
796
933
Base
20mm PVC
Scale 1:10
0 1 2 3 4 5 6 7 8 9 10


455
980
2mm deep countersink circles
Top
Bottom
Left
Right
Frame attached to the underside of the table-top
160
1257
5mm deep countersink square
450
270
120
240
Frame attached to clear perspex
10mm PVC
0
1
2
3
4
5
6
7
8
9
10
Scale 1:10


270
1360
Place-holders
White | 3mm aluminum
560
380
Revolving top & Lift
White | 3mm aluminum
0
1
2
3
4
5
6
7
8
9
10
Scale 1:10

Appendix B Evaluation Assessment Sheets

B.1 Computer Network Protocols Evaluation Assessments

B.1.1 OSPF knowledge pre-session evaluation questions

Student ID:	

1. An OSPF DR was taken offline due to a hardware fault. What series of events will follow this occurrence?

   ____

   ____

   ____

2. Explain the fault-tolerance mechanism of OSPF.

   ____

   ____

   ____

3. What is the name of the protocol used for neighbour discovery in OSPF?

   ____

   ____

   ____

4. What is the main purpose of the DR and BDR and what issue does it attempt to address?

   ____

   ____

   ____

5. What specific IP address is used to send an OSPF message to a DR/BDR?

   ____

   ____

   ____

6. List the OSPF states involved in establishing an adjacency.

   ____

   ____

   ____

7. How many packet types are used by OSPF?

____

____

____

8. Name two OSPF packet types.

____

____

____

9. Explain the purpose of the 'Priority Number'.

____

____

____

10. Why does the BDR use a timer?

____

____

____

B.1.2 OSPF knowledge post-session evaluation questions

Student ID:	

A. How would you rate your **level of interest** within the last session?

☆	☆	☆	☆	☆
Low				High

B. How **new** for you was the **content covered** within the last session?

☆	☆	☆	☆	☆
Very new				Very familiar

C. How **easy was it to understand** the content covered within the last session?

☆	☆	☆	☆	☆
Very easy				Very difficult

D. How **confident are you** on the content covered within the last session?

☆	☆	☆	☆	☆
low				High

1. What protocol is used to discover routers in OSPF?

____
____
____

2. What are the requirements needed for two routers to set-up neighbourhood?

____
____
____

3. What influences does a ‘Priority Number’ = 0 has on a router?

____
____
____

4. How often are hello packets sent and why are they used?

____
____
____

5. What is the default ‘Priority Number’ of a router?

____
____

6. What is the common ratio of a dead-timer in OSPF? Why is it used?

____
____
____

7. Why are DR / BDR needed and in which instance can they be employed?

____
____
____

8. What IP address is used between all OSPF participating routers?

____
____
____

9. Describe with the aid of suitable diagrams the sequence and process states to establish Neighbourhood in OSPF?

____
____
____

10. Explain the sequence and process of electing DR and BDR routers? Provide details of the algorithm used

____
____
____
____
____
____

E. How easy was it to remember **detail**-oriented questions correctly? (Example questions **5, 6, and 8**)

☆ ☆ ☆ ☆ ☆

Very easy Very Difficult

F. How easy was it to remember **process**-oriented questions correctly? (Example questions **9, 10**)

☆ ☆ ☆ ☆ ☆

Very easy Very difficult

G. How easy was it to remember **concept**-oriented questions correctly? (Example questions **2, 3, and 7**)

☆ ☆ ☆ ☆ ☆

Very easy Very difficult

H. What are your general comments on the session attended?

____

____

____

____

____

____

I. What do you believe was the most helpful / fruitful aspect of the session?

____

____

____

____

____

____

B.2 Database Evaluation Assessments

B.2.1 Sample Normalisation knowledge evaluation MCQs

Student ID:	

Normalisation is performed on databases to:

☑ Minimize data redundancy
☐ Create a relationship between data
☐ Keep multiple copies of data

Normalisation is performed on databases to:

☑ 1 NF ☑ 2 NF ☐ 3 NF ☑ 4 NF

A one-to-many relationship is

☐ A relationship between two tables, where a single row in one table is linked to a single row in another table
☑ A relationship between two tables, where multiple rows in a child table can be linked to a single row in parent table
☐ A relationship between two tables, where multiple rows in one table is linked to multiple rows in another table

The primary key is selected from:

☐ Composite keys
☐ Determinants
☑ Candidate keys

A relation in this form is free from all modification anomalies:

☐ First normal form
☐ Second normal form
☑ Third normal form

In the ________ normal form, a composite attribute is converted to individual attributes.

☑ First
☐ Second
☐ Third

A table on the many side of a one-to-many or many-to-many relationship must: ☐ Be in Second Normal Form (2NF) ☐ Be in Third Normal Form (3NF) ☑ Have a composite key
Tables in second normal form (2NF): ☐ Eliminate all hidden dependencies ☐ Have a composite key ☑ Have all non-key fields depend on the whole primary key
Which form simplifies and ensures that there is minimal data aggregates and repetitive groups: ☐ First normal form ☐ Second normal form ☑ Third normal form
Which form is based on the concept of functional dependency? ☐ First normal form ☐ Second normal form ☑ Third normal form

B.2.2 Problem-based question

Normalise the following data to into the Third Normal Form (3NF) and draw the resultant Entity Relationship Diagram (ERD) for this database structure.

Employee ID	Employee Name	Employment Date	Annual Salary	Title ID	Title Name	Dept. ID	Dept. Name
14	John Smith	14-Jul-11	14800	DV	Driver	N	North
45	David White	22-May-15	25700	MC	Mechanic	S	South
23	Matthew Brown	08-Nov-09	18500	DV	Driver	S	South
28	Paul Black	05-Mar-13	22300	MC	Mechanic	N	North

B.3 Queueing Theory Evaluation Assessments

B.3.1 Queueing theory knowledge pre-session evaluation questions

Student ID:	

1. Give 3 examples of where queueing theory might be used.

____

____

____

2. What does λ (lamda) symbol mean in queueing theory?

____

____

____

3. What is used to represent service rate? _____________________________

4. What's the difference as far as queueing theory goes, between finite and infinite system? What would be a realistic system?

____

____

____

5. What are the basic components which make up a queueing system?

____

____

____

6. What determines the time a person waits in the queue?

____

____

____

7. What do you understand by the term "utilisation" parameter of a queueing system? And what would be the 2 major variables to make up the formula?

   ____
   ____
   ____

8. Queueing theory relies on the mathematical concept of probabilities. If we have a λ value of 8 and μ value of 2, what do you think will occur the most?

   ____
   ____
   ____

9. The simplest queueing system is an M/M/1 Queue model. How would this model be written if it was made with 3 servers?

   ____
   ____
   ____

10. What do C and K represent in an M/M/C/K notation?

    ____
    ____
    ____

11. In an M/M/1 notation what would be the value of K (buffer)?

    ____
    ____
    ____

12. What notation would the following formula represent?

$$\pi_0 = \left[\sum_{k=0}^{c} \frac{\lambda^k}{\mu^k k!} + \frac{\lambda^c}{\mu^c c!} \sum_{k=c+1}^{K} \frac{\lambda^{k-c}}{\mu^{k-c} c^{k-c}}\right]^{-1}$$

____

____

____

13. How would a typical Poisson graph be drawn? And what would be the y and x axis parameters? Sketch your idea below.

B.3.2 Queueing theory post knowledge post-session evaluation questions

Student ID:	

1. Where do you think queueing theory is used? (give examples)

   ____
   ____
   ____

2. Where do you think queueing theory is used? (give examples)

   ____
   ____
   ____

3. What does µ (mu) symbol mean in queueing theory? ___________________

4. In queueing theory, what's the difference between finite and infinite systems? Give an example of a realistic System.

   ____
   ____
   ____

5. What are the major components of a queueing theory?

   ____
   ____
   ____

6. What determines the time a person waits in the queue?

   ____
   ____
   ____

7. What does "utilisation" parameter of a queueing system mean? What would be the 2 major variables to make up the formula?

   ____
   ____
   ____

8. Queueing theory relies on the mathematical concept of probabilities. If we have a λ (lamda) value of 10 and a λ (Mu) value of 1, what do you think will occur the most?

9. An M/M/1 Queue model is the simplest queueing system. How would this model be written if it was made with 3 servers?

10. In an M/M/C/K notation, would do C and K represent?

11. What is the que size in an M/M/1 notation?

12. What notation would the following formula represent?

$$\pi_0 = \left[\sum_{k=0}^{c} \frac{\lambda^k}{\mu^k k!} + \frac{\lambda^c}{\mu^c c!} \sum_{k=c+1}^{K} \frac{\lambda^{k-c}}{\mu^{k-c} c^{k-c}}\right]^{-1}$$

13. How would a typical Poisson graph be drawn? State what the y and x axis parameters would represent. Sketch your idea below.

14. What is a Poisson distribution?

____
____
____

A. The objects representing fiducials, were they intuitive enough?

____
____
____

B. Was it easy to figure out where the fiducials had to be placed on the screen?

____
____
____

C. Was the GUI understandable enough?

____
____
____

D. Did you find the counters and values displayed in various parts of the screen useful?

____
____
____

E. Was the animation easy to follow?

____
____
____

F. Did the prototype entice you to use it?

____
____
____

G. In the end this exercise was to enhance the way the queueing theory is thought and also to teach the user queueing theory.
Do you think you now have a better understanding of queueing theory?

____
____
____

H. What is your opinion about learning queueing theory aided by this prototype versus the traditional teaching method?

____
____
____

B.4 Multi-threaded Evaluation Assessments

B.4.1 Multi-threaded Task Scheduling pre-session evaluation questions

Student ID:	

1. What do you understand by the term multi-threading?

____
____
____

2. How do you identify between a thread and a process?

____
____
____

3. Is it possible for other threads to be empty when the main thread has executing processes scheduled?

____
____
____

4. When is it feasible to use multi-threading?

____
____
____

5. What are the advantages of multi-threaded programming?

____
____
____

6. Give an example of a process dependency scenario?

____
____
____

7. Does process dependency affect multi-threaded task scheduling? Explain your answer.

____

____

____

8. What do you understand by thread priority?

____

____

____

9. How are CPU resources affected by thread priority?

____

____

____

10. What effect do priority values impart on multi-threaded task scheduling?

____

____

____

B.4.2 Multi-threaded Task Scheduling post-session evaluation questions

Student ID:	

1. Give a brief explanation of multi-threaded programming?

____
____
____

2. Exemplify the difference between a process and a thread?

____
____
____

3. How can you adopt multi-threaded programming?

____
____
____

4. What are the effects of thread priority?

____
____
____

5. Is multi-threading always effective? Give reasons for your answer

____
____
____

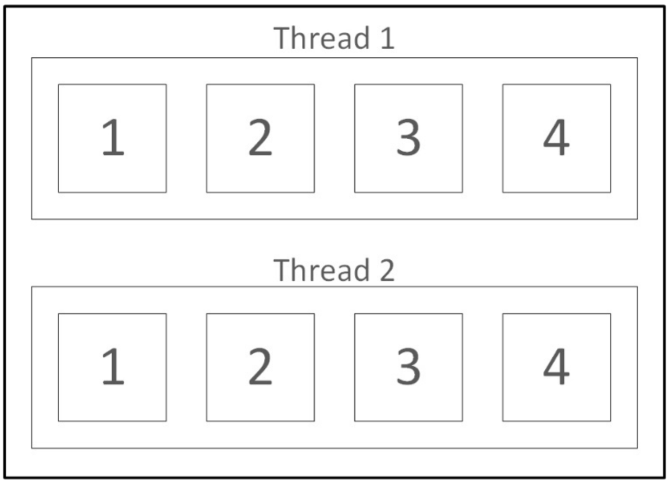
6. Does multi-threading effect application performance? Explain your answer

____
____
____

7. What are process dependencies?

8. From your understanding of multi-threaded task scheduling, how do dependencies effect programming development principles?

9. The following is a simple scenario that consists of two threads, Thread 1 and Thread 2, each having four processes scheduled:



Can process 3 on thread 2 execute before process 2 in thread 1?

9. Considering process 1 on thread 1 and process 1 on thread 2, how will these compile on execution

☐ Process 1 on thread 1 will execute before process 1 on thread 2

☐ Process 1 on thread 2 will execute before process 1 on thread 1

☑ Processes run simultaneously

☐ None of the processes will execute

B.5 Search-Space Evaluation Assessments

B.5.1 Search-space knowledge pre-session evaluation questions

Student ID:	

11. What do you understand by the term 'Search Space'?

____
____
____

12. Why is a Search Space needed?

____
____
____

13. What are the First and Last States called?

____
____
____

14. What is the process called when a state is revisited? And why would you need to do this?

____
____
____

15. What is a Ply in terms of a Search Space?

____
____
____

16. Do you know of any scenarios where a Search Space can be used? If so, mention up to 3?

____
____
____

B.5.2 Search-space knowledge pre-session evaluation marking sheet

1. What do you understand by the term 'Search Space'?
   - Model Answer: A search space is the set or domain through which an algorithm searches.
   - Total of 2 marks available:
      i. 2 marks for mentioning searching through a domain

2. Why is a Search Space needed?
   - Model Answer: A search space is needed to explore the possibilities of a given task/problem.
   - Total of 2 marks available:
      i. 1 mark for mentioning searching/exploring/going through
      ii. 1 mark for mentioning all the possibilities/solutions/states of a solution

3. What are the First and Last States called?
   - Model Answer: Start/Initial State and Goal State.
   - Total of 2 marks available:
      i. 1 Mark for each Correct State mentioned

4. What is the process called when a state is revisited? And why would you need to do this?
   - Model Answer: Backtracking is used to go back to a previous state in order to follow an alternative possibility.
   - Total of 2 marks available:
      i. 1 Mark for mentioning Backtracking.
      ii. 1 Mark for mentioning its purpose of moving back to a previous state in case of a dead end or in the hopes of finding a new path

5. What is a Ply in terms of a Search Space?
   - Model Answer: Ply is a row of states or a search exploration level.
   - Total of 2 marks available:
      i. 2 Marks for mentioning 'level' or 'row' of states

6. Do you know of any scenarios where a Search Space can be used? If so, mention up to 3?
      i. Total of 3 marks available: 1 Mark for every scenario mentioning any Problem-Solving scenario/game such as; chess, checkers, tic tac toe, battleships, ludo, go, missionaries and cannibals

B.5.3 Search-space knowledge post-session evaluation questions

Student ID:	

10. What is a Search Space?

____
____
____

11. What are the first and last states known as?

____
____
____

12. What is backtracking and why is it required?

____
____
____

13. What is a Ply in terms of a Search Space?

____
____
____

14. Do you know of any scenarios where a Search Space can be used? If so, mention up to 3?

____
____
____

15. Did you encounter any dead ends whilst constructing the Search Space? What did you do?

____
____
____

16. Did you manage to explore the entire Search Space?

____
____
____

17. Is there only 1 path or more than 1 path that could have been taken to reach the last state?

____
____
____

18. Is a Search Space useful? Why?

____
____
____

B.5.4 Search-space knowledge post-session evaluation marking sheet

1. What is a Search Space?
    - Model Answer: A search space is the set or domain through which an algorithm searches.
    - Total of 2 marks available:
        i. 2 Marks for mentioning searching through a domain

2. What are the first and last states known as?
    - Model Answer: Start/Initial State and Goal State.
    - Total of 2 marks available:
        i. 1 Mark for each Correct State mentioned

3. What is backtracking and why is it required?
    - Model Answer: Backtracking is used to go back to a previous state in order to follow an alternative possibility.
    - Total of 2 marks available:
        i. 1 Mark for mentioning searching/exploring/going through
        ii. 1 Mark for mentioning all the possibilities/solutions/states of a solution

4. What is a Ply in terms of a Search Space?
    - Model Answer: Ply is a row of states or an search exploration level.
    - Total of 2 marks available:
        i. 2 Marks for mentioning 'level' or 'row' of states

5. Do you know of any scenarios where a Search Space can be used? If so, mention up to 3?
    - Total of 3 marks available:
        i. 1 Mark for every scenario mentioning any Problem-Solving scenario/game such as; chess, checkers, tic tac toe, battleships, ludo, go, missionaries and cannibals

6. Did you encounter any dead ends whilst constructing the Search Space? What did you do?
    - Total of 2 marks available:
        i. 2 marks for mentioning the term backtracking

7. Did you manage to explore the entire Search Space?
    - Model Answer: No.
    - Total of 1 mark available:
        i. 1 Mark for knowing that more states were available for exploration

8. Is there only 1 path or more than 1 path that could have been taken to reach the last state?
    - Model Answer: No, there is more than 1 path to reach a goal.
    - Total of 2 mark available:
        i. 2 marks for stating that there is more than 1 path

9. Is a Search Space useful? Why?
    - Model Answer: A search space is needed to explore the possibilities of a given task/problem.
    - Total of 2 marks available:
        i. 1 Mark for mentioning searching/exploring/going through
        ii. 1 Mark for mentioning all the possibilities/solutions/states of a solution

B.6 Object-Oriented Evaluation Assessments

B.6.1 Object-oriented knowledge pre-session evaluation questions

Student ID:	

1. In your own words, can you describe what OOP is? How confident are you in explaining the concept of OOP?

   ____
   ____
   ____

2. List 2 foundational concepts of OOP.

   ____
   ____
   ____

3. Can you describe what a class in OOP is?

   ____
   ____
   ____

4. What is an object in OOP?

   ____
   ____
   ____

5. Describe the concept of Abstraction in OOP

   ____
   ____
   ____

6. Describe the concept of Instantiation in OOP

   ____
   ____
   ____

7. Can you explain what is happening in the code below and list the outcome?

```
public class Student
{
      String name;
      Int age;
      String course;
}
public void main (String ARGS[])
{
      Student s1 = new Student();
      s1.setName("Owen");
      s1.setAge(24);
      Student s2 = new Student();
      s2.setName("Twanny");
      s2.setAge(27);

      System.out.println(s2.name + "" + s1.age);
}
```

____

____

____

B.6.2 Object-oriented knowledge post-session evaluation questions

Student ID:	

1. Can you name 2 fundamental concepts of OOP?

   ____
   ____
   ____

2. What is an abstract class?

   ____
   ____
   ____

3. What is instantiation?

   ____
   ____
   ____

4. What is inheritance?

   ____
   ____
   ____

5. Describe an object in OOP.

   ____
   ____
   ____

6. What are the main benefits of OOP?

   ____
   ____
   ____

7. If you had to come up with a common (abstract) class, what properties would you include? Please write in code style.

```
    public class Student
    {
          String name;
          String nationality;
          String course;
          int age;

          public void study()
          {
                ……
          }
          public void haveCoffee()
          {
                ……
          }
    }
    public class Teacher
    {
          String name;
          String nationality;
          String subjectTaught;
          String carModel;
          Int age;

          public void teacherClass()
    {
          ……
    }
    public void explainLesson()
    {
    ……
    }
}
```

___

8. Create code inside the main function to instantiate a student, set his name and print it on screen.

```
public class Student
  {
        String name;
        int age;
        String course;
  }
  Public void main (String ARGS[])
  {
```

____

____

____

____

____

```
}
```

A. How confident are you in your answers to questions 1 and 6 being correct?

☆ ☆ ☆ ☆ ☆

Low High

B. How confident are you in your answers to questions 7 and 8 being correct?

☆ ☆ ☆ ☆ ☆

Low High

C. How confident are you in your answers to questions 2, 3, 4 and 5 being correct?

☆ ☆ ☆ ☆ ☆

Low High

B.7 ANN Evaluation Assessments

B.7.1 Sample ANN knowledge evaluation questions

Student ID:	

1. Can you name three types of Nodes in an ANN?

____

____

____

2. Why is a Hidden Layer used in an ANN?

____

____

____

3. What defines a Synapse and a Weight?

____

____

____

4. What is the use of an Activation Function?

____

____

____

5. Why is the Input of an ANN customized?

____

____

____

6. Why is the Output of an ANN customized?

____

____

____

7. How does adding more Hidden Layers affect data?

____

____

____

8. Why are the Weights customized?

____

____

____

9. What happens every time the data passes through Synapse?

____

____

____

10. What determines the result at the Output node stage?

____

____

____

11. Why is the result difference of the Expected Output and Actual Output important?

____

____

____

12. What is Back Propagation and why is it used?

____

____

____

Detail Focused	Questions 1, 3 and 12
Procedural	Questions 5, 6 and 8
Theoretical	Questions 2, 4, 9 and 10
Problem-based	Questions 7 and 11

B.7.2 Usability questionnaire

Statement	Strongly Disagree				Strongly Agree
It was simple to use the system	☆	☆	☆	☆	☆
I feel comfortable using the system	☆	☆	☆	☆	☆
I am able to efficiently complete my work using the system	☆	☆	☆	☆	☆
I can effectively complete my work using the system	☆	☆	☆	☆	☆
I am able to complete my work quickly using the system	☆	☆	☆	☆	☆
It was easy to learn to use the system	☆	☆	☆	☆	☆
I easily remember how to use the system	☆	☆	☆	☆	☆
I believe I became productive quickly using the system	☆	☆	☆	☆	☆
Whenever I make a mistake using the system, I recover easily and quickly	☆	☆	☆	☆	☆
The information provided for the system is easy to understand	☆	☆	☆	☆	☆
The information is effective in helping me complete the tasks and scenarios	☆	☆	☆	☆	☆
The organization of information on the system screens is clear	☆	☆	☆	☆	☆
I can use the system without written instructions	☆	☆	☆	☆	☆
I like using the interface of the system	☆	☆	☆	☆	☆
I can use the system successfully every time	☆	☆	☆	☆	☆
I am satisfied with this system as a whole	☆	☆	☆	☆	☆

B.8 ROS Evaluation Assessments

B.8.1 Post-test ROS knowledge evaluation sheet

Student ID:	

1. What is ROS?

____
____
____

2. Which operating system is required for a ROS Master to host a ROS architecture?

____
____
____

3. Is it possible for a single ROSCore to support multiple nodes?

____
____
____
____

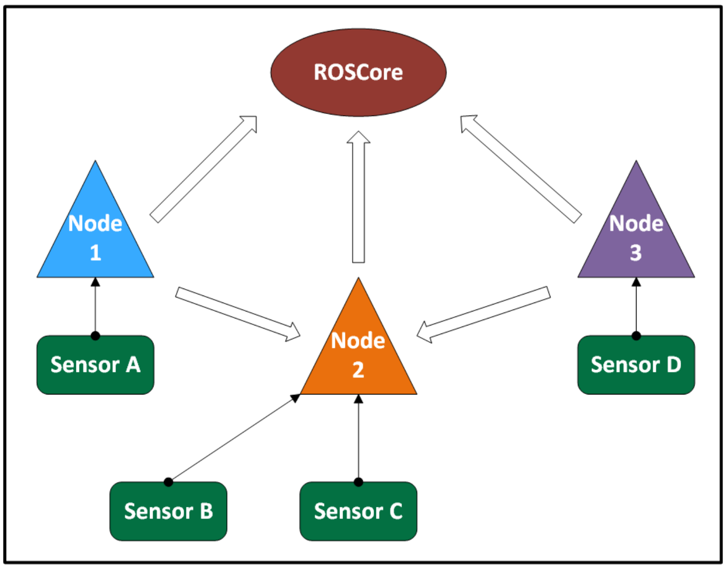
4. What is the purpose of a topic between nodes?

____
____
____
____

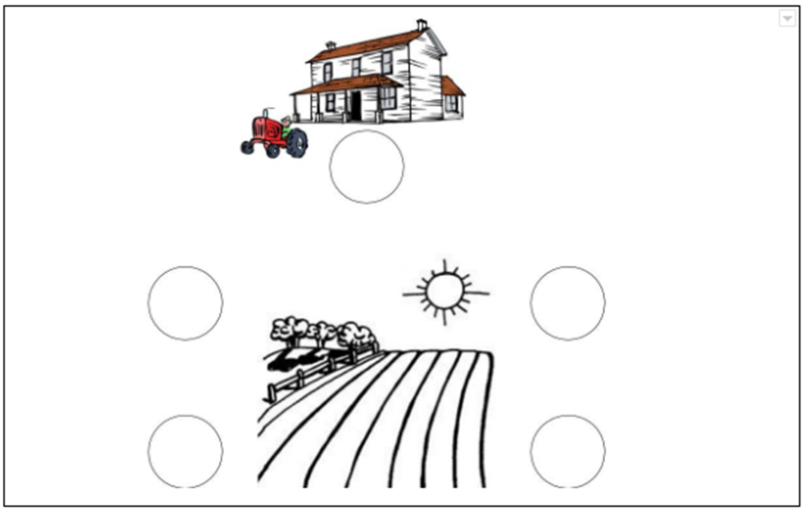
5. What do you understand by the term “publisher”? Can a publisher have multiple subscribers?

____
____
____
____
____

6. Identify from the below topology which of the links are called topics? *(circle accordingly)*



7. In the below scenario, you are required to design a ROS-based sensor network for a farmer who is concerned about his soil becoming regularly dry. The system should analyse soil via a humidity sensor and water the field accordingly to retain a constant moisture level. Furthermore, real time CCTV footage should be captured by a camera which the farmer can manoeuvre remotely using pan/tilt capabilities. Complete the below diagram with your designed ROS architecture.



Detail Focused	Questions 1 & 3
Procedural	Question 2
Theoretical	Questions 4 & 5
Problem-based	Questions 6 & 7

Appendix C TAM4Edu Evaluation Forms

C.1 Preliminary Evaluation of TAM4Edu Constructs

TAM4Edu: A Technology Acceptance Model for Educational Technology

Dear participant,

The aim of this study is to model technology acceptance of educational technology in higher education.

Kindly provide your personal view on the technology usage you have experienced during the lecturing session you have just attended.

Thank you for your cooperation.

* Required

1. **Ethical Consent** *

Check all that apply.

- [ ] I have read and signed the Ethical Approval Form as provided by the research investigator
- [ ] I agree to participate in the data collection of this study based on my personal experience in using education technology

2. **MDX ID / Name if unavailable** *

____

3. **Type of Technology Used**

Mark only one oval.

- ◯ Tangible User Interface
- ◯ PC based Software
- ◯ Traditional Lecture using only Projector/Smart-board

4. **Gender:**

Mark only one oval.

- ◯ Male
- ◯ Female

5. **Age:**

____

6. **Year of study:** *

Mark only one oval.

- ◯ Undergraduate year 1
- ◯ Undergraduate year 2
- ◯ Undergraduate year 3
- ◯ Postgraduate

7. TAM4Edu Evaluation Survey *

Mark only one oval per row.

	1. Strongly Disagree	2. Moderately Disagree	3. Somewhat Disagree	4. Neutral	5. Somewhat Agree	6. Moderately Agree	7. Strongly Agree
1. I wasn't able to learn the subject effectively through the technology used.	◯	◯	◯	◯	◯	◯	◯
2. The used technology should be made available after lecturing hours.	◯	◯	◯	◯	◯	◯	◯
3. Technology in general makes me nervous.	◯	◯	◯	◯	◯	◯	◯
4. The actual process of using this lecturing technology was enjoyable.	◯	◯	◯	◯	◯	◯	◯
5. The used technology permitted me to interact with my class mates.	◯	◯	◯	◯	◯	◯	◯
6. It is easy for me to remember how to perform tasks using the technology.	◯	◯	◯	◯	◯	◯	◯
7. The output quality I have got from this technology was high.	◯	◯	◯	◯	◯	◯	◯
8. I could tell when the lecturing technology was waiting for my input.	◯	◯	◯	◯	◯	◯	◯
9. The technology / system sensed my movements.	◯	◯	◯	◯	◯	◯	◯
10. The feedback from interacting with the system was intuitive.	◯	◯	◯	◯	◯	◯	◯
11. I was able to finish the given task using the technology without supervision.	◯	◯	◯	◯	◯	◯	◯
12. I needed someone to show me how the technology functions first.	◯	◯	◯	◯	◯	◯	◯

	1. Strongly Disagree	2. Moderately Disagree	3. Somewhat Disagree	4. Neutral	5. Somewhat Agree	6. Moderately Agree	7. Strongly Agree
13. This educational technology is not suitable to study with.							
14. Operating the educational technology was intuitive.							
15. I was able to fulfil all given tasks using the operators available.							
16. Technology in general makes me feel uneasy.							
17. The used educational technology was boring.							
18. I find the use of such technology as important in my studies.							
19. I find the information from the educational technology used to be very intuitive.							
20. The used technology was rather difficult to operate.							
21. Using the educational technology was relevant to my studies							
22. I felt very attentive during this lecture.							
23. The results obtained from the technology were intuitive.							
24. The inbuilt helping tips, helped me finishing the task effectively.							
25. The procedures used on the technology replicated the ones I use on my personal devices (tablets, smartphone etc.).							

	1. Strongly Disagree	2. Moderately Disagree	3. Somewhat Disagree	4. Neutral	5. Somewhat Agree	6. Moderately Agree	7. Strongly Agree
26. Through the lecturing technology I have learned to work in a team.							
27. The feedback I have received from the lecturing technology made my experience enjoyable.							
28. The lecturing technology promoted discussion and collaboration with classmates.							
29. The operators (mouse, keyboard, TUI, etc.) felt natural to use							
30. I waited a long time to get feedback from the educational technology.							
31. I have gotten distracted during the lecture.							
32. Learning how to perform tasks using the technology was easy							
33. The lecturing technology used in this lesson should be used regularly.							
34. I have no problem with the quality of the technology's output.							
35. Through this lecture I would characterise myself as being concentrated.							
36. The technology used in this lecture helped me understand the subject effectively.							
37. The lecturing technology used today enabled me to better understand abstract material.							

	1. Strongly Disagree	2. Moderately Disagree	3. Somewhat Disagree	4. Neutral	5. Somewhat Agree	6. Moderately Agree	7. Strongly Agree
38. Educational technology (interactive boards, PCs, etc.) do not scare me.							
39. I felt comfortable using the educational technology.							
40. I had fun using the educational technology.							
41. I look forward to using the same technology again in the near future.							

8. **Were there any questions that you felt uncertain with ? If so, can you please identify the question numbers.**

9. **Please add any comments about the Educational Technology used**

Powered by Google Forms

C.2 TAM4Edu Evaluation Framework

TAM4Edu: A Technology Acceptance Model for Educational Technology

Dear participant,

The aim of this study is to model technology acceptance of educational technology in higher education.

Kindly provide your personal view on the technology usage you have experienced during the lecturing session you have just attended.

Thank you for your cooperation.

* Required

1. **Ethical Consent** *

   Check all that apply.

   - [ ] I have read and signed the Ethical Approval Form as provided by the research investigator
   - [ ] I agree to participate in the data collection of this study based on my personal experience in using education technology

2. **MDX ID / Name if unavailable** *

   ____

3. **Type of Technology Used**

   Mark only one oval.

   - ◯ Tangible User Interface
   - ◯ PC based Software
   - ◯ Traditional Lecture using only Projector/Smart-board

4. **Gender:**

   Mark only one oval.

   - ◯ Male
   - ◯ Female

5. **Age:**

   ____

6. **Year of study:** *

   Mark only one oval.

   - ◯ Undergraduate year 1
   - ◯ Undergraduate year 2
   - ◯ Undergraduate year 3
   - ◯ Postgraduate

7. TAM4Edu Evaluation Survey *

Mark only one oval per row.

	1. Strongly Disagree	2. Somewhat Disagree	3. Neutral	4. Somewhat Agree	5. Strongly Agree
1. The lecturing technology used today enabled me to better understand abstract material.	⬭	⬭	⬭	⬭	⬭
2. I find the use of such technology as important in my studies.	⬭	⬭	⬭	⬭	⬭
3. The actual process of using this lecturing technology was enjoyable.	⬭	⬭	⬭	⬭	⬭
4. The lecturing technology promoted discussion and collaboration with classmates.	⬭	⬭	⬭	⬭	⬭
5. The feedback from interacting with the system was intuitive.	⬭	⬭	⬭	⬭	⬭
6. I was able to finish the given task using the technology without supervision.	⬭	⬭	⬭	⬭	⬭
7. Learning how to perform tasks using the technology was easy	⬭	⬭	⬭	⬭	⬭
8. I needed someone to show me how the technology functions first.	⬭	⬭	⬭	⬭	⬭
9. I felt comfortable using the educational technology.	⬭	⬭	⬭	⬭	⬭
10. Operating the educational technology was intuitive.	⬭	⬭	⬭	⬭	⬭
11. The used educational technology was boring.	⬭	⬭	⬭	⬭	⬭
12. Technology in general makes me nervous.	⬭	⬭	⬭	⬭	⬭
13. I find the information from the educational technology used to be very intuitive.	⬭	⬭	⬭	⬭	⬭
14. The used technology was rather difficult to operate.	⬭	⬭	⬭	⬭	⬭
15. Using the educational technology was relevant to my studies	⬭	⬭	⬭	⬭	⬭
16. I felt very attentive during this lecture.	⬭	⬭	⬭	⬭	⬭

	1. Strongly Disagree	2. Somewhat Disagree	3. Neutral	4. Somewhat Agree	5. Strongly Agree
17. I wasn't able to learn the subject effectively through the technology used.	⬭	⬭	⬭	⬭	⬭
18. Performing tasks using the technology is intuitive	⬭	⬭	⬭	⬭	⬭
19. The used technology permitted me to interact with my class mates.	⬭	⬭	⬭	⬭	⬭
20. Overall, I find the technology easy to use	⬭	⬭	⬭	⬭	⬭
21. The lecturing technology used in this lesson should be used regularly.	⬭	⬭	⬭	⬭	⬭
22. Through this lecture I would characterise myself as being concentrated.	⬭	⬭	⬭	⬭	⬭
23. The technology used in this lecture helped me understand the subject effectively.	⬭	⬭	⬭	⬭	⬭
24. I look forward to use the same technology again in the near future.	⬭	⬭	⬭	⬭	⬭

8. **Were there any questions that you felt uncertain with ? If so, can you please identify the question numbers.**

____

9. **Please add any comments about the Educational Technology used**

____

____

____

____

____

Appendix D Interview Guide Framework

D.1 Questions for an in-depth interview

Participant ID:	

1. Can you provide an overview of your role at Middlesex University?

2. What modules are you usually responsible for lecturing? In what programme of study?

3. A threshold concept is commonly considered a core concept which once understood transforms the way of thinking and understanding a subject. Can you identify any pertinent threshold concepts within your subjects?

4. What are the difficulties usually experienced in delivering this threshold concept in class?

5. Can you elaborate on the technical characteristics of this concept which present an added difficulty to teach and learn?

6. What pedagogical strategies do you usually adopt when teaching such concepts? Can you provide some examples?

D.2 Probes for in-depth interviews

Echo	Repeat the last statement and ask the participant to continue
Neutral	Encouraging: “I see” / “uh-huh”
Direct	“Please elaborate more on that”
Clarifying	You said …., please describe what you mean by that
Detail	What? How? Why?