UX EVALUATION OF VR LOCOMOTION & VIRTUAL OBJECT INTERACTION MECHANICS

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KEYWORDS

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ABSTRACT

Virtual Reality (VR) Interactions like in Ready Player One? Locomotion (LOC) and Virtual Object Interaction (VOI) are two key areas of concern, when designing and developing VR games and other VR applications. This paper describes a study of three interaction modes and their underlying VOI and LOC mechanics, using a range of consumer-oriented VR input setups, spanning from gamepad, over Spatially Tracked Hand Controllers, to Controllerless Hand Tracking and Omnidirectional Treadmill. All corresponding mechanics were implemented in the specifically developed, optimized and polished "real-world" game Gooze, to test them in a real-world scenario with corresponding challenges in gaming and human computer interaction. A within-subjects experiment with 89 participants using qualitative and quantitative analysis methods was conducted. The interaction modes and their mechanics were evaluated based on the four User Experience aspects: Player Enjoyment, Support of Gameplay, Simulator Sickness and Presence, with the latter being subdivided into the four sub-parameters: General Presence, Spatial Presence, Involvement and Experienced Realism, according to the igroup Presence Questionnaire. The paper concludes with summarizing the individual advantages and disadvantages of the assessed interaction modes.

INTRODUCTION

Ready Player One is a picturized novel about a near future society, in which most of their citizens try to escape the semiderelict real world by diving into the Virtual Reality (VR) software "OASIS" (Cline 2011). This story presented impressive ways to traverse through and interact with VR. Still, when designing and implementing VR games and other VR applications, typical concerns relate to the important topics of Locomotion (LOC) and Virtual Object Interaction (VOI). Likewise, those areas are often associated with the broad field of User Experience (UX) and very diverse input devices. On the basis of three consumer-oriented hardware setups and their underlying VOI and LOC mechanics, the following experiment will explore the four UX aspects: Player Enjoyment (PE), Support of Gameplay (SoG), Presence and Simulator Sickness (SimSick). Assessing Presence is based on the igroup Presence Questionnaire (IPQ), which outputs the four subscales General Presence (G), Spatial Presence (SP), Involvement (INV) and Experienced Realism (REAL, igroup 2016). As a Virtual Environment (VE), the specifically developed, optimized and polished "real-world" game Gooze was used.

RELATED WORK

The following will expand previously illustrated related literature (Wiedemann et al. 2017) with more recent works. Generally, our experiment is backed by a rather large number of 89 subjects, compared to the mentioned studies below.

Locomotion

One of the most important aspects of VR Locomotion lies in designing mechanics, which support the main concept of the application, while trying to reduce SimSick to a minimum. A very important factor related to this is the "vection" effect (Riecke and Feuereissen 2012 and Yao 2014), which can have a negative impact on users in this regard.

The study by Nabiyouni et al. investigates the navigational speed and accuracy of different VR Locomotion techniques (2015). They compared "fully natural" (real walking), "semi-natural" and "non-natural" (via gamepad) Locomotion methods, by their usage speed and accuracy (Nabiyouni et al. 2015). The semi-natural technique is based on walking in some kind of large-scale spherical hamster wheel, the "Virtusphere" (Nabiyouni et al. 2015). The study has shown that natural "high-fidelity" and well-designed non-natural "low-fidelity" techniques can outperform semi-natural "medium-fidelity" Locomotion mechanics (Nabiyouni et al. 2015). They argue that their results were "an effect of interaction fidelity", but they also requested more research with differently designed semi-natural techniques, because of the Virtusphere's downsides related to its mass and friction (Nabiyouni et al. 2015). This seems reasonable, as one might expect the spherical shape of the Virtusphere to influence navigation accuracy and its mass and friction to affect acceleration. These aspects are not included amongst the issues of the Omnidirectional Treadmill, investigated in our study.

Concerned with "the effect on cognition" or the "knowledge, understanding and application, and higher mental processes" regarding a VE, the study by Zanbaka et al. compares four different virtual "travel techniques" (2005). Additionally, Zanbaka et al. evaluate their effect on Presence (2005), using the "Steed-Usoh-Slater Presence Questionnaire" (Usoh et al. 2000). Three of the four Locomotion methods were tested using a VR Head Mounted Display (HMD) and included: "Real Walking (RW)" in a space, which has the same size as the virtual one (4.5 x 4.6 m2). “Virtual Walking using Six-Degrees-of-Freedom Tracking (VW6)” in a restricted physical space (1.2 x 1.2 m2), so the user can still naturally move within the confined space but needs to use joystick buttons to move forward or backward beyond the restrictions alongside the user’s looking direction. “Virtual Walking using Three-Degrees-of-Freedom Tracking (VW3)” which also uses joystick buttons to move and the same restrictions as VW6, but without the possibility to physically move within the bounds. Finally, the fourth method “Joystick with a Monitor (M)” was Non-VR and required the participant to sit in front of a computer screen and use a joystick to control movement and view direction in an arguably more conventional manner (Zanbaka et al. 2005). Their results regarding cognition unsurprisingly suggested that real walking in a “large tracked space” shows advantages over “common virtual travel techniques”, if “evaluation of information is important or … opportunity to train is minimal” (Zanbaka et al. 2005). In contrast, the results on Presence surprisingly could not show any significant differences between any of the three VR methods. Zanbaka et al. could only report a significant difference between the real walking and the joystick/monitor condition. Our experiment did not specifically evaluate any effects of Locomotion mechanics on cognition, but the qualitative results highlight those mechanics, that required more concentration of untrained participants. Regarding Presence ratings, our experiment clearly showed significant and detailed differences between the three tested VR Locomotion mechanics.

The study by Cherep et al. investigated “implications of teleporting” on “spatial cognition” (2019). They compared real walking (“concordant”) with two teleport mechanics: One mechanic without (“partially concordant”) and one with (“discordant”) the ability to control the view direction or rotation before the teleport takes place (Cherep et al. 2019). Their results showed an increase in spatial cognition error from the concordant to the partially concordant and from the latter to the discordant mechanic. In other words, spatial cognition declined from real walking over teleport without rotation control to teleport with rotation control (Cherep et al. 2019). The teleport mechanic (with rotation control) in combination with room scale tracking of real walking, examined in our experiment, confirmed these results, as in minor cases, it showed signs of disorientation in untrained users. Especially, when they misused the rotation control. Nevertheless, it was overall regarded as enjoyable and intuitive. What differentiates our experiment is including an omnidirectional treadmill as a Locomotion mechanic and using the real-world game Gooze as a platform, which evaluates Locomotion in combination with Virtual Object Interaction, instead of a pure experimental application, which lacks real-world challenges.

In their study, Shanmugam et al. developed a framework to “both navigate and interact with objects in virtual worlds”, while only using a low-cost Google Card-board VR system, without any external sensors or hand controllers (2017). They investigated the UX of three Locomotion mechanics in combination with a simplified Virtual Object Interaction mechanic. For Locomotion Shanmugam et al. implemented their own “Walk in place” mechanic and tested it against previously established “Look down to Move” and “Click to Move” mechanics (2017). Whereas to interact with virtual objects, a timer driven reticle was implemented. Once the reticle would hover long enough over an object for the timer to run out, a single pre-defined action with the object would be triggered. Their Walk in Place Locomotion mechanic scored best amongst the other two Locomotion mechanics (Shanmugam et al. 2017). In contrast to their study, our experiment did not only compare the UX of several Locomotion, but also of different Virtual Object Interaction mechanics, which additionally offered more versatile and sophisticated interactions. Furthermore, our study was aimed at high-end consumer hardware, while still maintaining a broad range of rather common setups, covering different investment costs.

Virtual Object Interaction

The two studies by Tian et al. (2018) and Holl et al. (2018) are both concerned with more natural appearing methods of grabbing and holding virtual objects in real-time using the Leap Motion controller as an interface. The approach by Tian et al. uses machine learning and particle swarm optimization in an offline process to pre-compute “stable grasp configurations” based on the possibly complex 3D models of the hands and objects (2018). During runtime, these stable grasp configurations are then used in combination with “dynamics/non-penetration constraints” and “motion planning techniques to compute plausible looking grasps” (Tian et al. 2018).

Aiming at a similar goal, Holl et al. used a very different approach, not requiring a pre-computational step. Their solution uses a physics method, based on the Coulomb friction model running in a performance efficient way (Holl et al. 2018). This enables simulating many types of dexterous interactions between hands and objects (e.g. spinning objects between fingers), while using a common VR engine (Holl et al. 2018). Both approaches are pushing VOI further towards the high fidelity of interacting with objects in reality and illustrate an area in which our study was limited, due to the range of assessed input devices. Investigating VOI in a more holistic manner, we used a simpler approach, based on a single grab/pinch parameter and snapping the object into the hand, while transitioning both to pre-defined poses.

EXPERIMENT METHODOLOGY

The following will describe the adjusted and refined design of the previously outlined experiment (Wiedemann et al. 2017). Its aim was to investigate several UX aspects of different interface mechanics in a “real-world” scenario with corresponding challenges in gaming and human computer interaction. Three interaction modes (also referred to as Combined Modes or modes) were primarily compared, each including one specific mechanic for VOI and one for LOC. However, we were also interested to see if users could distinguish how the VOI and LOC mechanics individually contributed to the different UX parameters. The experiment task required the participants to move through the VE and interact with virtual objects at the same time. Accordingly, they completed separate, but almost identical VOI and LOC questionnaires after each mode. The VOI and LOC scores were then averaged to produce a single set of scores per condition.

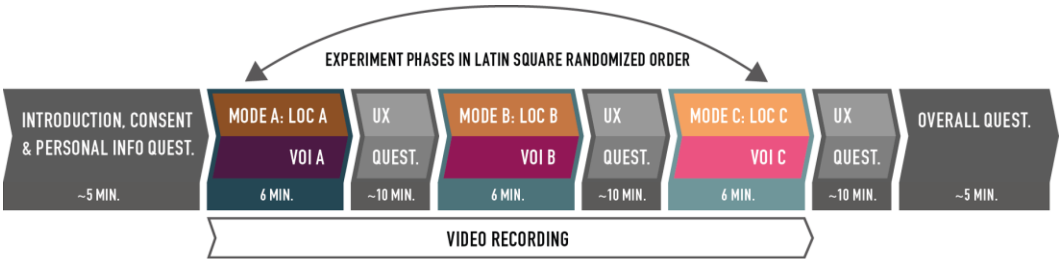


Figure 1: Experiment Phases and Procedure

In the within-subjects design, using quantitative and qualitative evaluation methods, each participant went through the following procedure (see Figure 1): After being informed about health and safety, the participant consented to the experiment procedure and the appropriate and ethical use of the collected data. Following this, the subject filled out a questionnaire on personal information, e.g. age, gender, handedness and subjective experience with VR and digital games. The participant then played the game Gooze (see Figure 2), using three different interaction modes (i.e. Mode A, B and C, see Figure 4) and evaluated them one after the other. The individual mode order was pseudo randomized based on Latin square sequences and each mode would last for six minutes, with a visible countdown for the player. The subject was given the task, to solve the puzzle of escaping the virtual room. The solution was to “break off” (grab) a loose bedpost, carry it over to the door with the rusty padlock, “break it apart” (touch it with the bedpost) and open the door (see Figure 3). So, the user needed to move through the virtual room and interact with certain objects by controlling virtual hands (e.g. inspect, grab, direct, carry and use). After solving the puzzle, the level would reload and the player would be instructed to keep on moving, interacting and generally playing around until the timer runs out. The available level was the same one for each mode. After a mode ended, the participant could rest, while parallelly filling out the side-by-side VOI/LOC double questionnaire on the previous experience. Each individual questionnaire included four sections: Player Enjoyment and Support of Gameplay (two 7-point Likert scales), Presence based on the validated IPQ (14 7-point Likert scale items, igroup 2016), two optional qualitative free text questions for specific individual feedback and a Simulator Sickness scale (from 0 to 10). After evaluating all three modes, one last general questionnaire had to be filled out, with one final optional free text field for any sort of feedback (see Figure 1). Additionally to the questionnaire data, all play test sessions were video recorded, to analyze verbal remarks or retrace specific behavior. A common Windows PC ran Gooze at steady 90Hz and the Oculus Rift CV1 was used as a HMD with three sensors for roomscale tracking (~3x3 meters) and two Oculus Touch controllers as Spatially Tracked Hand Controllers (STHCs, Oculus 2019). A standard wireless Xbox One controller (Microsoft 2019) was used as a gamepad. To provide Controllerless Hand Tracking (CHT), a Leap Motion controller (Leap Motion 2019) was mounted to the front of the HMD. Finally, a Wizdish ROVR 1 (Wizdish 2019) was used as an Omnidirectional Treadmill.

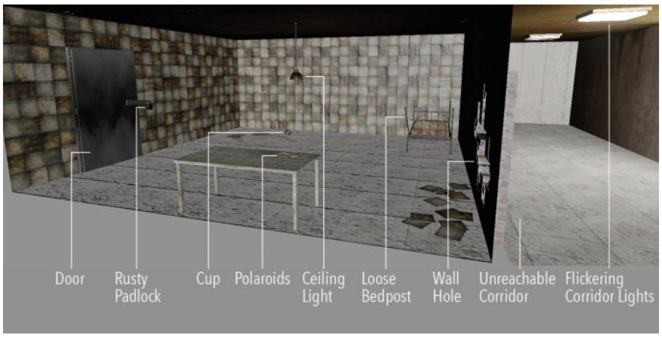
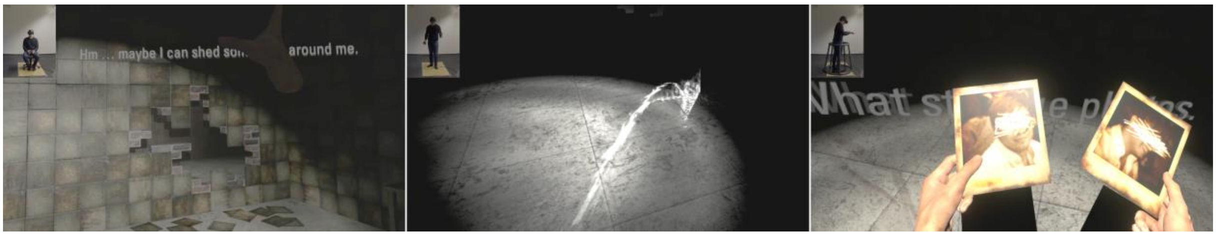


Figure 3: Gooze Development Screenshot: The Level with its various Objects

The Game: Gooze

Gooze is a polished horror puzzle game, optimized for VR and specifically developed for this study over several iterations, using the Unity game engine (Wiedemann et al. 2017 and Unity 2019). The playable level in the experiment is designed as a virtual room escape game. In this rather dark room, the player can move around freely and explore the horrifying environment and several interactable objects. To escape, the player needs to break off the loose bedpost and use it to break apart the rusty padlock to open the door (see Figure 3). To get to this solution, the naive user first needs to explore the dark corners of the room: either by walking there and waiting until the view becomes brighter (involving the physical eye adjustment and an implemented auto exposure effect), or by grabbing and directing the ceiling light towards an area of interest. To give the player subtle hints, the player



a) b) c)

Figure 2: Gooze In-Game Screenshots: a) Holding and Directing the Ceiling Light via Gamepad, b) Activated Teleport Parabola with the Arrow on the Floor Showing the Direction the User Wants to Look at, after the Teleport via STHCs and c) Holding and Inspecting Polaroids via CHT

character's thoughts are visualized as subtitles, which temporarily fade in, once the player looks at certain objects (see Figure 2a).

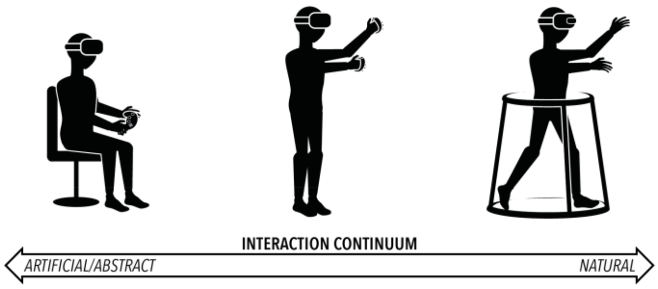
Interaction Modes

The three assessed interaction modes have been deliberately selected from nine theoretically possible combinations of the implemented VOI and LOC mechanics. The selection was based on previous experience through pre-studies. Likewise, design and implementation were informed by previous development iterations (Wiedemann et al. 2017). Each interaction mode makes use of different input hardware to cover a broad range of possible consumer setups with diverse requirements, e.g. like investment costs and available physical play space. The combinations of mechanics make the most of the affordances offered by the hardware interfaces in a meaningful way. E.g. it is more sensible to map the character movement onto an analogue stick on the gamepad, instead of the action buttons. Likewise, the combinations of input devices are not awkward or obstructive to use in parallel and instead provide a reasonable usability. E.g. using the gamepad together with the treadmill would hinder the player to comfortably grab the treadmill's handlebar for balance. Additionally, the mode selection provides seated and standing experiences, as these are typical VR gaming scenarios. Finally, the selected interaction modes map to three rather discreet points on the interaction continuum between artificial/abstract and more natural human computer interactions (see Figure 4). E.g. to grab with a virtual hand in Mode A, one needs to pull a gamepad trigger, whereas in Mode C one just naturally performs the gesture with a physical hand. Or to virtually move forward in Mode A, one steers a gamepad's analogue stick, whereas in Mode C one just slides the physical feet back and forth.

It needs to be emphasized, that the results of this study are intrinsic to the selected interaction modes and their specific design, implementation and configuration. Nevertheless, assumptions can be extracted and transferred to similar setups and even non-gaming VR scenarios, which require the user to virtually move and interact with virtual objects.

Mode A: Gamepad

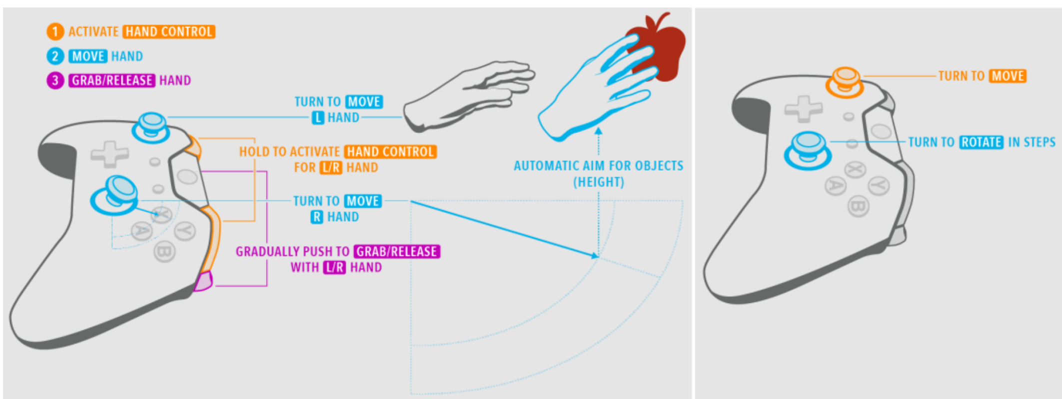
Mode A uses the most artificial/abstract interaction mechanics in this study. To provide a very common gaming scenario, the player is seated, in this case on a regular swivel chair. This provides freedom to physically look around, rotate and e.g. lean forward and sideways. On the other hand, this locks the player to a fixed position, which in turn does not require a large physical play space (see Figure 4a). In this mode, the participant uses a common gamepad to control VOI and LOC.



a) b) c)

Figure 4: Interaction Modes a) Mode A: LOC and VOI via Gamepad, b) Mode B: LOC via Physical Walking & Teleport with STHCs and VOI via STHCs and c) Mode C: LOC via Treadmill and VOI via CHT

To control the movement of the left virtual hand on the X-Z axes, the user needs to hold the left bumper and steer the left analogue stick. This behavior is mirrored for the right subcontrols, respectively (see Figure 5a). A non-trivial aiming system will automatically interpolate the Y position of the hand, according to surrounding interactable objects. The user can neither actively control the rotation of the hands nor perform any finger specific gestures. To grab an interactable object, the respective trigger needs to be pressed (see Figure 5a). This will gradually transition the regular hand pose to a fist, when there are no grabbable objects in range, or to a pre-defined corresponding grabbing pose. This grabbing pose automatic and the related snapping of a grabble object into the hand in an equally pre-defined "optimal" pose helps users to identify distinct object grabs while providing a clear visual and software-physical experience. This approach was implemented into all three modes in individually optimized variations (see Figure 2a and c). If a hand collides with an object, grabs it or a grabbed object collides with another object Mode A further provides the user with haptic feedback via various types of gamepad vibrations.



a) b)

Figure 5: Mode A Control Schemes for Participants a) for VOI and b) for LOC

When not pressing the left shoulder bumper, the player is able to virtually move through the VE via steering the left analogue stick (see Figure 5b). When the right shoulder bumper is not pressed, the user can rotate his view along the Y axis in distinct 33-degree steps using the right analogue stick (see Figure 5b). This “snap rotation” was chosen over continuous rotation, to avoid SimSick. Additionally, the participant was able to physically rotate with the swivel chair in a continuous manner.

Mode B: Spatially Tracked Hand Controllers
Mode B uses a combination of abstract and rather natural mechanics. In this mode, the player is standing and can naturally move within a ~3x3 meters play area (see Figure 4b). In turn, a rather large physical play space is required, as well as an alternative abstract method for Locomotion (i.e. teleportation). This is due to the fact, that the VE in Gooze is larger, then the physical play area. The participant is given two STHCs, to control the VOI and the teleport LOC mechanics.

The positions and orientations of the virtual hands are automatically linked to those of the STHCs and thus the user’s hands. Via capacitive sensors in the sub-controls of the STCHs, physical gestures like thumbs up, pointing index fingers or “firing the handgun” are mimicked rather naturally. Similarly to Mode A, to make a virtual fist or grab a virtual object, the player can gradually press the respective grab trigger (see Figure 6a). Mode B also provides the user with haptic feedback via vibrations of the STHCs. Only in contrast to Mode A, the haptic feedback is correctly split between the corresponding hands.

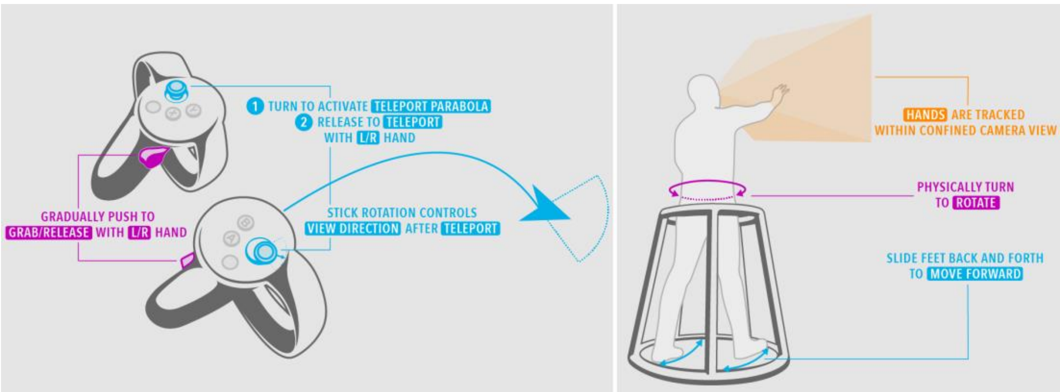
The participant’s head position and orientation will be mimicked quasi immediately. Hence, to virtually move, the player can naturally move in the physical play area. Although, when getting too close to the edge, a blue virtual grid temporally fades in, visualizing the area’s boundaries as a safety measure. In turn, due to the disparity between the virtual and the physical space, an additional teleportation mechanic was implemented, inspired by the one in Doom VFR (Bethesda 2019). Once the user steers one of the analogue sticks on the STHCs, a visual parabola fades in, connected to the corresponding hand. Its direction and length are controlled by naturally posing the respective hand. The point where it hits the floor is marked by an arrow (see Figure 2b), representing the exit position and direction the user wants to look at after the teleportation. The teleport is executed once the user lets go of the analogue stick. The arrow’s direction can be controlled by directing the analogue stick (see Figure 6a). The teleportable area is restricted by the walls of the room and the static objects like the bed and table (see Figure 3).

Mode C: Controllerless Hand Tracking & Omnid. Treadmill
Mode C uses the most natural combination of interaction mechanics assessed in this study. The player is standing in a stationary treadmill. This provides freedom to physically look around, rotate and lean in various directions. On the other hand, it does not require a large physical play space (see Figure 4c). No hand controllers are involved and both the VOI and LOC mechanics are controlled via the participant’s physical movements only.

This mode uses an infrared sensor, mounted to the front of the HMD (see Figure 4c), which tries to track skeletal representations of the user’s hands down to the bending of each finger joint. So, to grab a virtual object, the user just needs to physically move a hand and grab in mid-air. Similar to the other modes, once the grab or pinch threshold is passed, a close enough grabbable object will snap into the virtual hand in a pre-defined pose and the virtual hand pose will transition to the corresponding grab pose. To avoid unintendedly releasing an object by moving the hand out of the sensor frustum (see Figure 6b), a fallback system freezes the grabbing virtual hand to the last tracked position and orientation. This mode does not provide the user with any haptic feedback.

In this study, the assessed treadmill, requires the player to slide his or her feet back and forth to virtually move forward towards the looking direction. The device works as a microphone and provides only a single output parameter, the noise volume of the sliding feet. Hence, it does not support moving backwards or sideways, but still facilitates a close to natural physical movement to virtually move forward. A generically calibrated volume-to-speed curve was implemented, to compensate the none-linear relation between the volume of the sliding feet and their actual movement speed. It further applied a minimum volume threshold to avoid unintended forward motion, when turning around and thus creating noise.

An outline of the experiment can be viewed at the URL: https://vimeo.com/wiedemannd/uxevalvrlocvoi



a) b)

Figure 6: Control Schemes for Participants a) for Mode B and b) for Mode C

EXPERIMENT RESULTS

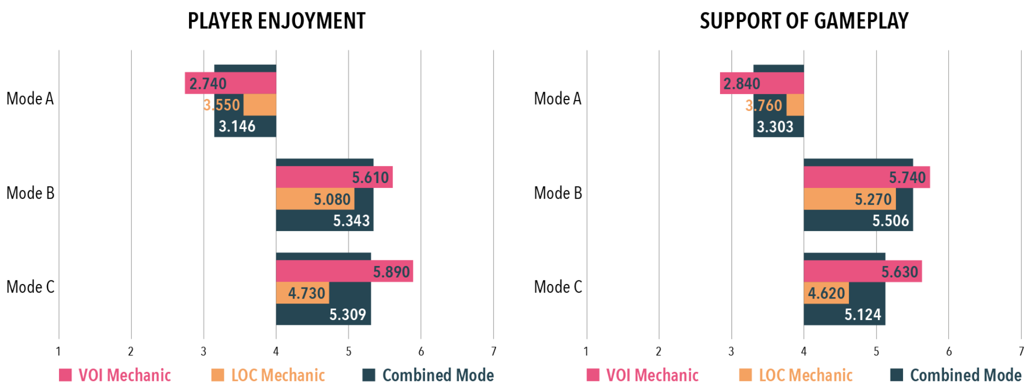
The experiment was conducted with 89 participants (total n = 89), who did not receive any compensation. Because of nausea, one participant (P32, participant ID) had to discontinue playing through Mode A, but fully completed the other two modes afterwards. The subjects consisted of 61 males and 28 females and their ages ranged from 20 to 78 years and averaged at 35 years. According to the statement "I am an experienced digital game player", 42 were rather inexperienced (< 4 on 7-point Likert scale) and 47 rather experienced (>= 4) subjects, with a mean of 3.888. 37 participants noted, they were playing digital games between "less than once a year" and "once every some months", whereas 52 noted they would play digital games between "once a month" and "every day". According to the statement "I have experience with Virtual Reality", 63 were rather VR inexperienced (< 4) and 26 rather experienced (>= 4) subjects, with a mean of 2.640. The analysis of the qualitative data was conducted similar to the "Thematic Analysis" approach (Braun and Clarke 2006), though the process was condensed into the following three phases: Read the data to become familiar with it, split the comments into thematically separated phrases or words, accumulate these phrases or words in thematic clusters and structure them hierarchically on the fly. To facilitate this process, we developed the free online qualitative analysis tool "Text Clusters Generator" (Wiedemann 2019) and used it in this study. Regarding the scores of UX aspects, we visually inspected associated VOI and LOC parameter histograms and found them to be approximately similar. So, to compare parameters for the three modes, illustrating the combined operating of VOI and LOC mechanics, the VOI and LOC scores were averaged to produce a single set of scores per condition, i.e. the "Combined Mode" values.

Player Enjoyment & Support of Gameplay

By conducting six non-parametric Friedman tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and b), we determined significant differences between the associated PE and the associated SoG scores across the VOI mechanics, the LOC mechanics and the Combined Modes. All p-values are < 0.0005. Post hoc analysis revealed statistically significant differences for the pairwise comparisons apart from scores between B and C, except for the SoG scores for LOC mechanics, which instead did not show a significant difference between LOC A and LOC C.

It is clear, that the VOI mechanics in general have the biggest impact on PE and SoG (see Figure 7a and b). Also, most participants did not get along very well with Mode A and in particular VOI via the gamepad. Around half of the participants regarded the overall controls of Mode A as "difficult" or even "obstructive" and negatively highlighted the overlapping input scheme of the VOI and LOC controls. This is likely due to the fact, that many participants had never used a gamepad before. In contrast, a couple of experienced players specifically advocated the sophisticated gamepad controls over the hands and interactions: "I like how I had to manually control the grabbing and moving, unlike most of the games that combine the entire process into a single button" (P62). Several players complained about the snap rotation feature to be "irritating" or "disorienting". Finally, the need for additional practice was mentioned multiple times, which is not surprising, regarding the 6-minute time limit.

Mode B's Combined Mode values either score on par (PE) or better (SoG) than Mode C. Around half of the participants described VOI via STHCs in positive terms like "easy", "enjoyable" and "intuitive". Moreover, several players illustrated their experience in similar words to: "The [STHCs] allowed me to interact with the virtual world in a very natural way" (P73). Although Mode B had the highest scores for LOC in PE and SoG, some participants' comments also showed a certain degree of reservation towards both physical walking and teleportation. Even though many described physical walking as being "intuitive", "realistic" and "freeing", others also addressed their concerns about being scared "to trip over the cable" (P48) and especially about the blue safety grid: "The blue grid often bothered me and made me change my plans." (P83). Nevertheless, there seems to be no practical alternative to a virtual safety system, when using a roomscale setup. Although the concept of walking and teleporting seems to require some practice, most users described teleportation positively as being "easy", "fun", "convenient" and "fast": "Teleportation helped me get where I want to be very fast" (P19), which is supported by the high PE and SoG scores. Nevertheless, some players also regarded it as "unrealistic", "less immersive" and sometimes "disorienting". The latter is likely due to the inexperience of some participants with the usage of analogue sticks. Inspecting the session recordings, it became clear, that some players did not fully understand the teleportation's rotation control. Thus, some participants teleported, while applying an unintentional and disorienting rotation and then physically turned around.



a) b)

Figure 7: Ratings of a) Player Enjoyment and b) Support of Gameplay

In Mode C, VOI via CHT was overall regarded positively by a majority of participants, which is supported by its PE scores. Users described the mechanic as “easy”, “intuitive”, “natural” and “immersive”. Furthermore, users highlighted the “detailed skeletal hand tracking” and how it “encourages interactions”: “I liked how precise the finger movements were shown” (P54) and “It encourages you to interact with [the] environment on [a] new [and] deeper level.” (P78). However, the SoG scores, which are slightly lower than the ones of VOI via STHCs, are likely due to the inherent limitations of the infrared tracking: “in-game hands did not always match the real hands” (P80) and “I dropped some objects unintentionally because I twisted my [virtual] hand.” (P42). Likewise, due to the limited tracking space, grabbing and directing the ceiling light was an issue for many participants. When a user wanted to look at the illuminated area, the grabbing hand would leave the tracking frustum and the hand freezing fallback system did not always perform in an optimal way. Another issue is connected to the handlebar of the treadmill, which restricted users from comfortably bending down to pick an object up. Although it was possible for most participants a minority with shorter extremities was completely obstructed by this: “I wasn’t able to pick up items from the floor” (P77). Finally, some users also complained about the lack of any haptic feedback, when grabbing and interacting in mid-air: “grabbing something with no resistance (e.g. feeling something in your hand) feels unnatural.” (P41). In comparison to Mode B, LOC via the treadmill clearly did not score well regarding PE and SoG. Almost a third of the participants commented the treadmill in a positive manner, using terms like “fun”, “intuitive” and even “natural”: “It's very close to feel like walking” (P04). Nevertheless, the majority of users described issues inherent to the device and its implementation. The concept of sliding your feet in the device was described as “slippery”, “insecure” and even “dangerous”: “it introduces a certain danger of slipping that you need to stay aware of” (P73). This may possibly be compensated with more practice. The sliding motion itself, coupled with holding onto the handlebar for support, on the other hand was regarded as “unrealistic” and “less immersive” by some participants: “Funny but not very realistic” (P20). The device’s capabilities of only supporting forward motion seemed to be a prominent and even “obstructing” issue with some participants, especially when they unintendedly overran a targeted position: “you [had] to turn 180 degrees, go back, then turn around again and approach the object very slowly.” (P42) and “the inability to move backwards strongly influenced my perception.” (P06). Around a quarter of the participants complained about the “lack of precision”: “Hard to make smaller steps and to navigate to a specific spot in the room.” (P47). Related to this is the problem of “turning around was often interpreted as walking forward.” (P75). These issues are due to the very simple microphone tracking of the device. To avoid SimSick a minimum volume threshold was implemented to prevent users from being unintendedly pushed forward, while only turning. In turn, this prohibits the tracking of fine-grained movements. Additionally, participants physically moved in very individual ways. Hence, the applied generic calibration of the mechanic did not optimally fit all users.

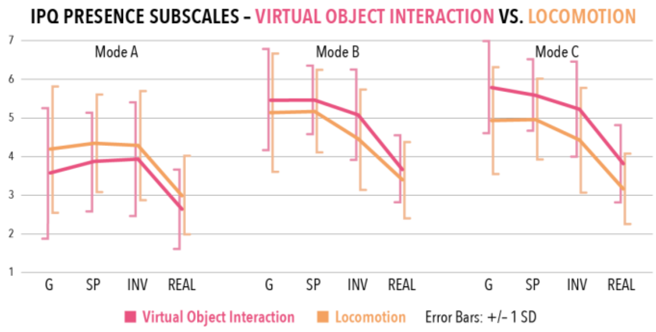


Figure 8: Graphs for IPQ Presence Subscales of VOI vs. LOC Mechanics

Presence

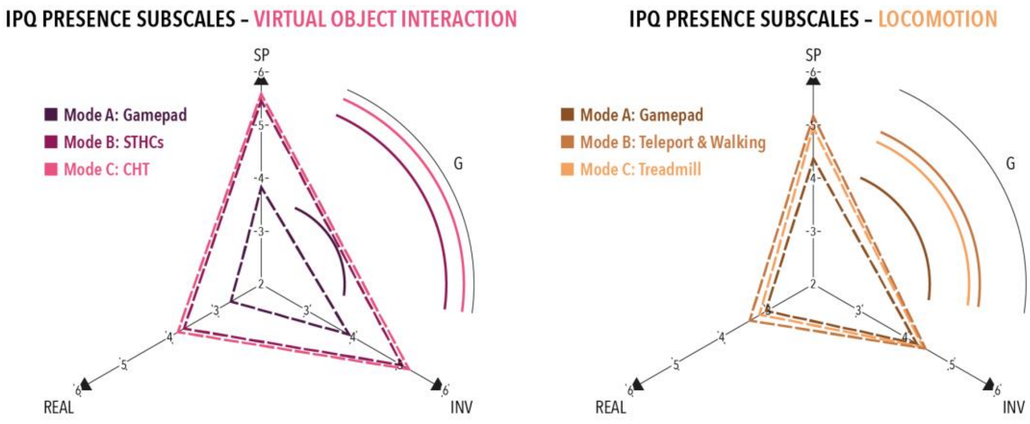
By conducting 12 non-parametric Wilcoxon Signed Rank tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and c), we determined significant differences between all associated VOI and LOC scores of the four IPQ Presence subscales (igroup 2016), across all three modes. Most p-values are < 0.0005, with “Mode B: VOI G - LOC G” having the highest value of $p = 0.013$, but also being the only p-value > 0.01. Visually inspecting the graph profiles in Figure 8 (based on Table 1), uncovers them to be very similarly shaped (similar bending without any intersections) and to provide an almost equal distance from VOI to LOC subscales, per mode. Hence, the data seems to suggest, that VOI and LOC affected Presence in separate ways and that participants could differentiate between the respective mechanics.

By conducting 12 non-parametric Friedman tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and b), we determined significant differences between the associated scores of the four IPQ Presence subscales (igroup 2016), across the VOI mechanics, the LOC mechanics and the Combined Modes, except for “LOC INV” ($p = 0.305$). All other significant p-values are < 0.0005, except for “LOC REAL” ($p = 0.028$). Post hoc analysis revealed statistically significant differences for corresponding pairwise comparisons apart from the scores between B and C and “LOC REAL” A and C.

Examining the VOI, LOC and Combined Mode Presence values (see Figure 9a, b and Figure 10a), only the sub-parameters “G”, “SP”, “INV” show fluctuating values, below and above the neutral score of 4. VOI clearly shows a greater impact on Presence than LOC, when inspecting the corresponding diagrams (see Figure 9a and b). Regarding the Presence structures of VOI mechanics, the gamepad is clearly outperformed by the STHCs and CHT, with the latter providing the deepest Presence feeling. This is likely due to the naturalness of CHT: “[CHT] did significantly contribute

Table 1: Mean ± SD of IPQ Presence Subscales for VOI and LOC Mechanics

Mechanic	G	SP	INV	REAL
VOI A	3,570±1,691	3,865±1,271	3,927±1,478	2,646±1,033
VOI B	5,480±1,315	5,476±0,889	5,096±1,176	3,683±0,870
VOI C	5,810±1,186	5,600±0,928	5,239±1,244	3,817±0,993
LOC A	4,190±1,630	4,344±1,263	4,303±1,414	3,008±1,015
LOC B	5,130±1,531	5,189±1,074	4,463±1,301	3,396±0,995
LOC C	4,930±1,380	4,980±1,057	4,433±1,364	3,163±0,909



a) b)

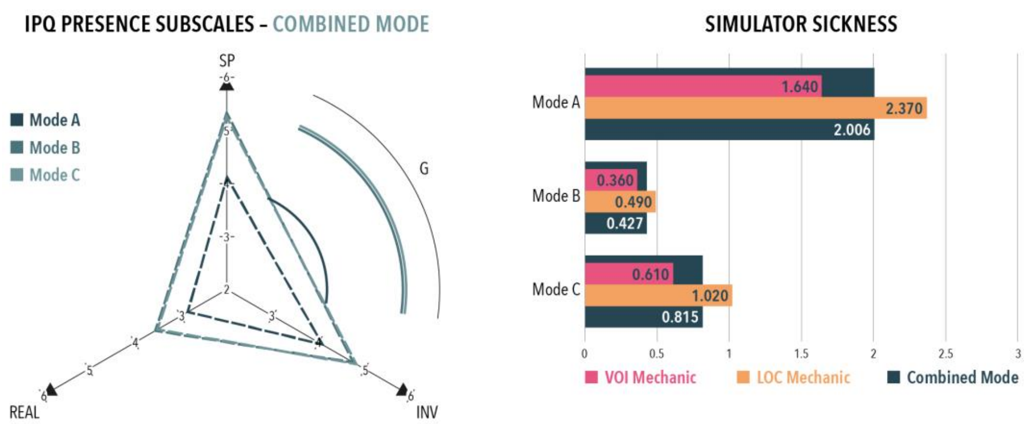
Figure 9: Ratings of IPQ Subscales for a) VOI and b) LOC Mechanics

to enhance the entire virtual reality journey." (P07). In terms of LOC, there are still differences, but not as distinct ones. Although it combined a very abstract with a very natural mechanic, Mode B's teleport and walking LOC mechanic seemed to provide the strongest Presence feeling: "it blends nicely the immersion of walking around" (P70) and "I sometimes forgot that I could just use my real physical movements to move around after I had been teleporting a lot." (P64). Examining the Combined Mode Presence diagrams (see Figure 10a), Mode B and C both provide a structure, almost identical in shape and strength. Hence, they seem to provide an equally strong and positive Presence feeling. In contrast, Mode A clearly scores worse, likely due to the complexity of the controls and the short time limit to get accustomed to them: "I was more concentrated on managing the Gamepad than I was on the game itself." (P88).

Simulator Sickness

By conducting three non-parametric Friedman tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and b), we determined significant differences between the associated SimSick scores across the VOI mechanics, the LOC mechanics and the Combined Modes. All p-values are < 0.0005. Post hoc analysis revealed statistically significant differences for corresponding pairwise comparisons apart from the scores between B and C.

LOC clearly shows a greater and more negative impact on SimSick than VOI, when inspecting the corresponding diagrams (see Figure 10b). Nevertheless, the effect of VOI on SimSick should not be ignored. Overall though, due to implementing LOC mechanics, specifically avoiding SimSick, very low levels could be reached. Although Mode A clearly shows the worst SimSick scores, it is interesting how LOC via gamepad was improved in this regard, comparing it with prior iterations (Wiedemann et al. 2017). This is likely due to the reduced speed and the combination of snap rotation with swivel chair rotation. The relatively high score for VOI via gamepad may be caused by naive users needing to concentrate a lot on operating the mechanic: "I had to think a lot about what button to release/press." (P70). In contrast, Mode B clearly shows the lowest SimSick, for both VOI and LOC. This seems due to the sub-mechanics not inducing any vection: "I can see the necessity of teleports due to motion sickness issues for new users." (P51). Mode C closely follows B, regarding SimSick. A certain disparity between foot motion and virtual movement and thus vection could not be entirely avoided. Nevertheless, physically moving the feet, greatly helped in reducing SimSick, compared to LOC via gamepad. However, this was likely not the case, when players tried to move into a different direction than forward: "Not being able to move backwards was disturbing." (P21). Minor SimSick through VOI via CHT may have been caused by incorrect tracking and attempting to reach correct tracking again.



a) b)

Figure 10: Ratings of a) IPQ Subscales for the Combined Modes and b) Simulator Sickness

CONCLUSION

How to achieve VR interactions like in Ready Player One (Cline 2011)? This paper illustrated implementing a highly optimized VR game or non-gaming application with sophisticated interaction requirements, while offering compatibility to a broad range of consumer-oriented hardware setups. The respective study assessing these VR setups and their underlying mechanics provided corresponding individual advantages and disadvantages related to UX and general requirements.

Mode A marks the low-end setup in this study, not requiring a large playing area and as a seated experience it provides a certain attraction for some users. However, it was outperformed in all assessed UX aspects. This is likely due to the limited inherent interface possibilities of the gamepad, which resulted in a complex input scheme requiring more adaptation time from users. Mode B comes with medium costs but requires a rather large playing area for roomscale tracking. It scored either on par or better than Mode C, regarding PE and SoG and was generally well accepted as rather intuitive and well-fitting for VR. Additionally, it induced a strong Presence feeling, while minimizing SimSick. Mode C marks the high-end setup in this study, also not requiring a large playing area and seemingly especially suitable for running applications. It performed either on par or slightly worse than Mode B regarding UX. The naturalness of CHT induced a very high Presence feeling. Nevertheless, both the hand and feet motion tracking devices revealed their limitations. Thus, VOI was not as robust and LOC not as precise or versatile, as the corresponding mechanics in Mode B.

Future research could include follow up experiments investigating the VOI and LOC mechanics separately. Furthermore, the mechanics could be further extended: e.g. by using more sophisticated grab methods, adding a calibration procedure to create individual ROVR profiles for user motion and body dimensions, adding a turning prediction to allow more fine-grained movements, using a more sophisticated treadmill altogether and further optimizing the fallback system handling grabbing hands leaving the sensor frustum.

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