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Investigating Social Cognition and Personal Space through Tactile Event-Related Potentials in Virtual Reality.

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Abstract:

Heightened neural responses to tactile stimuli over the somatosensory cortex in peripersonal space (PPS) have been found in previous research, with a similar enhancement occurring during social cognition. This heightened somatosensory response is indicative of the brain's sensitivity to respond to multisensory stimuli in the space immediately near the body, as well as to social stimuli, potentially demonstrating the brain's mechanisms to protect the body. However, not much research has investigated the somatosensory responses to tactile and social information simultaneously in different spatial contexts. As well as a lack of an investigation into these two processes together, there are clear methodological issues that have arisen from traditional on-screen methods in exploring this, namely the ecological validity of previous experiments. Therefore, this study aimed to apply a novel methodological approach using virtual reality (VR) and electroencephalography (EEG), to advance our understanding of embodied social cognition and its neural mechanisms at different distances. To do so, this study used VR to present pre-recorded videos, in which participants engaged in a social or perceptual task. The videos were presented either in their near distance (.95m) or far distance (3.45m) whilst participants received tactile stimulation on their right fingers. I expected heightened neural activity to tactile stimulation during the social task in the near distance. The experiment revealed early differences in the P45 event-related potential (ERP) component, with an increased amplitude in the presentation of stimuli in the near space compared to the far space. Later components, specifically the N140 and longer-latency effects, observed in the Nd1 component, revealed greater amplitudes during the perceptual task compared to the social task. The findings suggested increased neural activation when processing touch with spatial and social information, potentially providing evidence of embodied processing of social stimuli, which is sensitive to spatial contexts. However, future research is needed to explore whether this neural response is unique when carrying out a perceptual task in social contexts. Finally, the present study's use of VR highlighted a space for the integration of novel technology into research, for more applicable and ecologically valid findings.

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Contents:

1. Introduction

1.1 Electroencephalography (EEG) and Event-Related Potentials (ERPs)

The fast development of neuroimaging techniques, such as EEG, has allowed researchers to better explain the neural processes involved in several cognitive functions, such as attention (Luck, 2012). Measuring activity over time is an important aspect of doing so, which highlights a key advantage of using EEG due to its ability to measure millisecond electrical activity changes in the brain (Kappenman & Luck, 2011). EEG is a non-invasive technique, which provides portability and flexibility in terms of testing subjects in different environments (Hu & Roberts, 2020). It measures small electrical fluctuations in the electrical current between the scalp and the electrode, in which the signal is then amplified (Soufineyestani et al., 2020). These fluctuations typically occur as a result of internal or external events, such as responding to stimuli or decisions (Luck, 2012). EEG data is unable to localise activity in very specific regions of the brain, unlike its other neuroimaging counterparts such as functional magnetic resonance imaging (fMRI), resulting in poor spatial resolution, compared to its ability to measure millisecond changes in electrical activity in the brain, demonstrating its high temporal resolution (Longo et al., 2012). Despite this, EEG is useful in showing brain activity during events requiring processing, that are time-locked to a trigger, in which an ERP can be measured (Mannarelli et al., 2023). ERPs are the EEG signal locked to a specific event. Activity prior to the event, typically around 100ms, is considered to be at baseline. Multiple presentations within the same event category are presented and the signal locked to that event is averaged (Kappenman & Luck, 2011). The underlying assumption is that the brain signal of interest is phase-locked to the event and noise of a random phase. Therefore, averaging removes random noise and preserves the phase-locked signal (Kappenman & Luck, 2011). This isolates activity that has varied due to a presented stimulus. ERPs are typically reported by indicating whether there was a negative (N) or positive (P) peak, with the latency at which the peak appeared after the stimulus was presented (Kappenman & Luck, 2011). Despite the low spatial resolution, it is still possible to measure activity over larger areas of the brain, which are of interest. Furthermore, it is possible that using results from prior research, if an ERP is locked to the onset of a stimulus, which has previously shown that a region of the brain, like the somatosensory cortex is involved and responsible for the measured ERP, we can then infer that this region is involved in processing the stimuli given. ERP components have been linked to cognitive processes and can be linked to these processes. For example, the N170 component, which appears in the visual cortex, is larger when subjects are presented with flashing images of faces on a computer screen compared to non-faces (Luck, 2012). Many researchers have used this component to address how face processing in the brain occurs (Kappenman & Luck, 2011). Moreover, processing multisensory stimuli often evokes ERPs in the somatosensory cortex, as does the engagement of social cognition (Ku et al., 2007; Masson & Isik, 2023). Analysis of such ERPs has allowed researchers to understand the brain regions potentially involved in sensory and social processes and what this looks like in typical, healthy brains. Therefore, highlighting the clinical implications of knowing what atypical activity in these processes may look like.

There is neural activity that is of interest that is not phase-locked but cannot be examined by the ERP, which requires a time-frequency analysis of the EEG data. Analysing changes in brain frequencies such as event-related desynchronisation (ERD) and event-related synchronisation (ERS) can help to reveal how different brain regions synchronise and desynchronise during processing in response to external events (Wamain et al., 2016). These are frequency-based oscillations in neural activity in specific frequency bands, compared to ERPs, which only reveal the timing of neural events. Mu rhythms are examples of these oscillations which occur in the sensorimotor cortex. Therefore, there is a clear space for the use of EEG measures in investigating sensorimotor activation due to the various information it can provide.

1.2 Touch and social touch in the brain

Touch is a vital part of social interaction, and activity has been measured across the somatosensory cortex when touch is felt (e.g., Masson & Isik, 2023; Peled-Avron & Woolley, 2022). It is thought that the ability to sense touch is developed prior to other senses, highlighting its importance (Gallese & Ebisch, 2013). The somatosensory cortex is composed of the primary and secondary somatosensory areas, both of which receive sensory-related inputs such as proprioception (the ability to sense movement, action, and the location of where stimuli are coming from), vision, and touch (Gallese & Ebisch, 2013). Ku et al. (2007) were interested in exploring the neural response to touch after they previously demonstrated an N140 somatosensory-related potential during working memory. This potential was evoked by tactile stimulation paired with a visual stimulus during a working memory task. The authors investigated this by pairing the presentation of a visual stimulus, a red light-emitting diode (LED) or a green light, with tactile stimulation or only presenting two tactile vibrations. During the presentation of the stimuli, two tasks were completed: a unimodal and a crossmodal task. In the unimodal task, each trial began with a tactile vibration (either high or low frequency), followed by a short delay, after which another tactile vibration was presented. Participants had to say whether the first and second vibrations were the same. The frequencies varied randomly between trials, and response times were recorded. In the crossmodal task, the sequence was the same, except the second stimulus was a visual cue (green or red LED) instead of a tactile vibration, with each LED pre-assigned to match specific vibration frequencies (e.g., green for high, red for low). At the end of each trial, participants indicated whether the LED matched the first vibration’s frequency. By running an

Independent Component Analysis (ICA) on their ERP data, they found enhanced independent components in the primary somatosensory cortex following the expectation of the second visual stimulus (Ku et al., 2007). Additionally, fMRI studies have also been able to highlight the involvement of the primary visual cortex when responding to tactile stimulation (Merabet et al., 2008). This supports the idea that crossmodal processes, such as perceiving touch and visual stimuli, modulate activity in the primary somatosensory cortex (Ku et al., 2007). Overall, past evidence has supported the idea that processing various stimuli from the external world results in multiple areas of the brain, particularly in the sensorimotor system, to work together, such as when processing visual stimuli and touch (Gallese & Ebisch, 2013). This is also known as multimodal processing. In this thesis, I presented an experiment that capitalises on the established changes in the somatosensory cortex in response to crossmodal stimuli.

Consistent with these findings, Jones and Forster (2012) examined how visual tasks influence somatosensory responses and tactile attention by investigating the modulation of tactile ERPs. Attention modulations were observed at the N80 and P100 components, with early N80 effects indicating specific exogenous attention mechanisms. The N80 ERP component is an early somatosensory response, meaning these effects reflect early sensory processing to external attentional demands, resulting in involuntary processing. Specifically, the P45, N80, P100, N140, and longer-latency effects (Nd1 and Nd2 components) were measured. An increase in the P100 component, which is also thought to reflect early attentional processes, confirmed early processing in the somatosensory cortex (Jones & Forster, 2012). Similarly, Jones and Forster (2013) later confirmed these findings and identified modulation of tactile ERPs when exploring how visual tasks affect somatosensory processing and tactile attention. The authors were firstly interested in identifying which stages of somatosensory processing are influenced during engagement in a visual task; and second, in observing the impact of increased visual load on correlates of tactile exogenous attention namely, orienting and selection. Endogenous attention is defined as being goal-directed and voluntary based on the processing of external stimuli and their properties, whereas exogenous attention is involuntary (Jones & Forster, 2013). To explore this, EEG was recorded as participants performed a tactile exogenous attention task. The subjects either watched a presentation of rapid serial visual stimuli (single task) or the same presentation but actively monitored it for targets (dual task). Jones and Forster (2013) suggested that an increase in visual load can alter the somatosensory processing of tactile stimuli, by which there is a reduction in the brain's ability to do so. This was shown by the N80, which was only modulated in the single-task and not in the dual-task. This indicates that both early somatosensory processing and tactile attentional selection mechanisms are impaired when simultaneously monitoring a visual stream (indicating a high load) during an exogenous attention task. Jones and Forster (2013) demonstrated how tactile information is processed in the brain by highlighting that somatosensory processing can be modulated by engaging in a visual task, particularly when it requires high attentional sources. These findings shed light on the interplay between different sensory modalities, indicating that sensory and attentional processing involves multiple systems and suggesting that the somatosensory cortex plays a role in multimodal integration. Furthermore, the use of EEG allowed the researchers to capture precise and millisecond changes in neural activity across these systems, highlighting its usefulness. However, the study only used one type of visual load task, which was the visual stream, meaning that there is limited applicability in how different visual tasks could impact somatosensory processing. For example, visual stimuli which involve real-life scenarios could elicit very different neural findings.

Social touch can be defined as the observation of physical contact between two or more people or the physical sensation itself in social interactions (Fahey et al., 2019). It is thought to play a critical role in human connection. Neural correlates have also been found in observed social touch due to the close relationship between the processing of vision, touch, and action (Deschrijver et al., 2016; Gallese & Ebisch, 2013). When watching others receive or give a social touch, it is thought that the brain maps out and forms an internal representation of the motor movement and sensory processes using our own relative processes (Peled-Avron & Woolley, 2022; Deschrijver et al., 2016). This can be linked to theories of embodied cognition through how the brain perceives and processes the actions of others.

1.3 Embodied Cognition

Theories of embodied cognition propose that cognitive processes are grounded in the body's interaction with the world, specifically through perception and action (Macrine & Fugate, 2020). It is argued that cognition is influenced by sensorimotor experiences with external stimuli, which lead to an integration of multimodal processes. This integration allows for the observation of an action to be processed as if the body were experiencing or performing the action itself by activating the same neural networks involved in carrying out the action (Macrine & Fugate, 2020). For example, FMRI studies have supported neural activation when observing touch and revealed activation in the primary somatosensory cortex when observing a hand being stimulated by an object and when this object is moving close to the observed hand (Gallese & Ebisch, 2013). EEG studies have also highlighted the neural underpinnings of embodied cognition, specifically when observing and feeling touch. For example, human studies have revealed a suppression of Mu rhythms when an external action is observed, such as seeing two people touch (Peled-Avron & Woolley, 2022). Mu rhythms are oscillations which occur within 8-12Hz in the sensorimotor cortex. Suppression of these rhythms has been linked to ERD caused by an increase in neural activity in sensorimotor areas (Perry et al., 2010). Additionally, the P45 is typically observed in the activation of the primary somatosensory cortex and has also been found to increase in amplitude (Peled-Avron & Woolley, 2022). Peled-Avron and Woolley (2022) identified an enhancement in this component when two people touching were presented, and this effect was especially heightened when it was presented from a first-person perspective. This heightened effect may suggest that the brain integrates observed touch more effectively when it perceives the observed action as occurring to oneself. A later P100 component was observed when this was presented from a third-person perspective, and this was linked to activity in the secondary visual cortex (Peled-Avron & Woolley, 2022). Similarly, the findings revealed a late positive potential (LPP), which was found following observed touch but was suggested to reflect social-emotional processes, which are thought to occur at a later stage. Moreover, a larger P3 component was found when subjects were presented with tactile stimulation on the same hand as a simultaneously observed touch on a human, compared to when it was observed on a wooden hand (Deschrijver et al., 2016). This highlights an interesting observation in which processing touch in other humans may result in higher neural activity compared to non-humans as it does not match one's own tactile information (Deschrijver et al., 2016). Despite the substantial body of evidence supporting the link between these ERP components and the brain's response to touch, it is important to note that one cognitive process should not be attributed to one area of the brain and instead, various regions of the brain are involved in somatosensory processing, as highlighted by fMRI studies (Peled-Avron & Woolley, 2022; Gallese & Ebisch, 2013). For example, the response to social touch requires the involvement of the early visual cortex and somatosensory cortex (Masson & Isik, 2023). Overall, it is evident that neural responses to touch may encompass the theory of embodiment, resulting in multimodal activity in the brain, with the somatosensory cortex being highly involved in responding to and processing felt touch as well as observed touch in social contexts. This is due to the involvement of vision, touch and perception in these observations.

1.4 Social Cognition

Social cognition is the ability to infer emotional states, experiences, and intentions of others, allowing appropriate responses to other's behaviours to be made (Sel et al., 2020). Similar to the perception of touch, embodiment in social cognition has been proposed (Wicker et al., 2003). Empathy is considered a key element of social cognition as it requires the ability to infer the emotions and intentions of others and to be able to relate to them (Schaefer et al., 2020). Schaefer et al. (2020) investigated whether trait empathy predicts activity in the primary somatosensory cortex whilst receiving tactile stimulation. This activity was measured using fMRI whilst participants were touched on their hands either by a rubber hand or a real hand. Trait empathy, which was measured by the Interpersonal Interactivity Index (IRI; Davis, 1980), was found to predict activity in this region when receiving touch from both the real and rubber hand. The authors suggest that those with higher trait empathy scores may attend more to their sensations and in turn to other's emotions (Schaefer et al., 2020). However, it is important to note that these findings were based on an exploratory correlation, meaning that a direct cause and effect between trait empathy and how the somatosensory cortex processes touch cannot be made. Despite this, these findings highlight an important area of study within social cognition to be studied specifically, the potential relationship between personality traits and embodied processing. Furthermore, this also highlights the clear role of the somatosensory cortex in the observation and embodiment of the emotions of others.

Both EEG and fMRI studies have outlined neural underpinnings, highlighting the internal mapping and representation of social cognition (Wicker et al., 2003). Wicker et al. (2003) revealed that the anterior insula was activated when people experienced and observed someone else experiencing disgust through fMRI. Moreover, when participants were asked to observe and imitate facial expressions, activity in areas, such as the premotor cortex and somatosensory cortex was seen, further supporting the idea that social cognition is an embodied process. Similarly, Pineda et al. (2009) suggested that the brain maps out observed facial expressions to the corresponding feelings. This mapping involves the same neural circuits which would activate if experiencing the same emotion as observed. This embodiment is evident in the engagement of sensorimotor areas when processing other people's emotions and sensations, such as disgust into one's own sensation (Gallese & Sinigaglia, 2018; Winkielman et al., 2008).

Tactile ERPs have also shown sensorimotor activation and have been used in conjunction with emotional visual stimuli to investigate the theory of embodiment (Gallese & Sinigaglia, 2018; Winkielman et al., 2008). For example, Sel et al. (2020) investigated this using an emotion discrimination task whilst receiving tactile stimulation on the left finger and toe. The specific location in which participants received tactile stimulation allowed the researchers to probe the right somatosensory cortex, which is thought to be more involved in processing emotions and emotional facial recognition than its left counterpart (Sel et al., 2020). The authors measured somatosensory-evoked responses (SEPs) by probing this area via tactile stimulation whilst the participants viewed angry, sad, or neutral faces. This examined whether the somatosensory cortex showed discrete somatotopic activations when observing other people's facial expressions. Additionally, visually evoked potentials (VEPs) were also measured specifically during facial processing. An ERP subtraction method was used to isolate somatosensory responses from visual processing, by subtracting the VEPs from SEPs. The study's findings revealed an increase in emotion-specific activation in the hand area of the somatosensory cortex during the observation of angry facial expressions compared to sad, which resulted in a decrease in activity (Sel et al., 2020). The somatosensory cortex may, in turn, exhibit distinct activations to different facial expressions, highlighting its role in emotional cognition. This was later confirmed by a study comparing the embodiment of emotional facial expressions in those with autism spectrum disorder (ASD) to typical humans (Fanghella et al., 2022). ASD is a neurodevelopmental disorder which often presents difficulties in social perception and discriminating between facial emotions (Fanghella et al., 2022).

Similar to Sel et al. (2020), the authors presented the two groups with pictures of faces displaying happy, neutral, and fearful faces whilst neural data was recorded. SEPs were also evoked using tactile stimulation following the presentation of the visual stimulus. The ASD group showed significantly reduced P100 SEP amplitudes during the emotion discrimination task, compared to the typical group, which revealed a reduced embodiment of emotions in the ASD group. Additionally, there were also differences in the N80 SEP component between the different emotions but only in the typical group. This further suggests a key role for the somatosensory cortex in social cognition in the typically developed human population, specifically in emotional processing. An interesting note to make is that whilst ASD has been commonly linked to lower trait empathy, which may explain the reduced P100 SEP amplitude during the emotion discrimination task, more recent research has highlighted that this may be an incorrect conclusion (Donaldson et al., 2022). Donaldson et al. (2022) investigated how well different measures of empathy could explain different scores on the Autism-Spectrum Quotient (AQ) using self-reported and lab-based measures. The researchers found that self-reported measures were better at predicting traits of Autism and highlighted inconsistencies in using lab-based measures. Therefore, findings on the link between empathy and ASD regarding the embodiment of facial expressions should be interpreted with caution.

A key point to consider is the use of the ERP subtraction method to isolate somatosensory responses, specifically subtracting the visual ERP from SEPs in these studies. While this can be useful to dissociate neural responses, some researchers, such as Tame and Longo (2020), have questioned its validity. For example, it has been questioned whether this method can be used when there are diverse neuronal sources, whether it can be extended to other types of stimuli, and whether this would only work if the stimuli (e.g. visual and sensorimotor) are completely separate (Tame & Longo, 2020). However, Galvez-Pol et al. (2021) have since defended this approach, suggesting a common activity in visual and sensorimotor responses and that it can isolate SEPs, including common activity. Additionally, earlier and later ERP components outside of the 200-300ms range, which is not typically expected if there is merely an overlap in activity, were identified, revealing meaningful sensorimotor processing. In the present study, I decided not to subtract the visual ERP as it was expected that there would be multimodal processing of visual and tactile information. This aligns with the embodied cognition theory, which tends to involve the integration of various sensory modalities such as visual and tactile senses. Therefore, separating them may not have reflected the processing of real-world experiences.

1.5 Spatial Attention in Peripersonal Space (PPS)

Endogenous attention can also be defined as a higher-order cognitive function that allows us to select information to prioritise and process (Jones, 2019). This process has been extensively researched in relation to the multisensory processing of stimuli presented at different distances from the body, a key element of spatial attention. PPS, the immediate space around the body, has been of particular interest due to its role in protecting the body (Sambo & Forster, 2009). Early studies on macaque monkeys found two sets of neurons that respond to stimuli presented at different distances from the body, which activate the somatosensory cortex and hold a representative map of the body (Rizzolatti et al., 1981; Holmes & Spence, 2004). One set was found to be activated by stimuli in the far distance and the other by stimuli close to the primate's body. Additionally, multisensory neurons that are receptive to visual stimuli are thought to fire at a faster rate to stimuli in near space (Rizzolatti et al., 1981; Holmes & Spence, 2004). PPS has also been defined as the space in which visuo-tactile events are coded for, following the finding that the firing rate of neurons responding to visuo-tactile stimuli was proportionally dependent on the distance that it was presented in (Teramoto & Kakuya, 2015). As a result, stimuli entering PPS are typically responded to faster (Cartaud et al., 2018).

Since the fast progression of a PPS neural network in macaque monkeys, the development of this evidence in humans has been much slower in comparison, underlining a need for further research. Teramoto and Kakuya (2015) confirmed a similar coding system in healthy human brains. The authors conducted a speed discrimination task where participants identified whether tactile stimulation was on their left or right hand, ignoring visual distractors. They calculated inverse efficiency (IE) scores, a combination of reaction times (RTs) and accuracy scores and found significantly higher IE scores in the 'near' condition when the visual and tactile stimuli were not presented on the same side, indicating poorer performance, but the opposite effect when they came from the same side. This is commonly referred to as the congruency effect (Serino, 2019; Longo et al., 2012). However, this was not found in the far condition (Teramoto & Kakuya, 2015). This suggests that visual distractors only influenced performance in the near condition, confirming the integration of visuo-tactile stimuli in PPS (Teramoto & Kakuya, 2015). Similarly, Sambo and Forster (2009) found that RTs to tactile stimuli are quicker when a visual stimulus is simultaneously presented close to PPS. This may suggest a protective purpose of PPS, with stimuli within this space being attended to faster to ensure that the body can defend itself in time if this stimulus is a threat (Kimura & Katayama, 2023). De Haan et al. (2016) supported this by showing participants an animation of a spider or butterfly approaching or moving away from their hands. Participants responded as quickly as possible to simultaneous tactile stimulation. Reaction times were faster when the stimulus was closer to the hand and approaching, especially if the stimulus was a spider and the participant was afraid of spiders. This underscores the protective function of PPS. The influence of approaching visual stimuli has been of interest due to its facilitation of spatial prediction of task-irrelevant tactile stimuli, emphasising the protective nature of the near space and its role in preparing for potential threats (Kimura & Katayama, 2023). An approaching threat requires early prediction of the actions needed to protect the body, which can be used to explain the early integration of stimuli entering this space (Kimura & Katayama, 2023).

Wamain et al. (2016) measured event-related-(de) synchronisation (ERD/S) of Mu rhythms while presenting objects in PPS or extra personal space. Participants completed a reachability judgement task and an object identification task. In the object identification task, participants had to judge whether an object was distorted or not and in the reachability task, they had to assess if it was reachable or not. The findings showed a difference in Mu rhythm desynchronisation as early as 300ms after the object was presented during the reachability task but not in the object identification task. This indicates that the activation of the neural network responsible for motor control is specifically related to making action-oriented decisions, such as judging reachability, rather than automatically triggered by the presence of objects. Furthermore, this activation was strengthened when the object was presented in PPS and weakened as the object was presented further away. Based on this, the authors suggested that the desynchronisation associated with the coding of visual stimuli is dependent on the location of where the object is presented, particularly if it is presented in PPS. Wamain et al. (2016) concluded that motor coding of visual objects is influenced by both their intrinsic properties (like manipulability) and their spatial location during tasks requiring action decisions (e.g. the reachability task). This means that the neural response to objects depends not only on their physical features and spatial context but also on the participant's intended interaction with them. This study also highlights the usefulness of measuring millisecond changes in neural activity as the analysis of Mu rhythm desynchronisation at different time points provided a sequence of neural events related to object perception and action planning. The key finding was that rhythms associated with sensorimotor processing, such as Mu rhythms, were modulated by the task demands at different distances from the body. Overall, the study provided evidence for the interaction between visual and motor processes, particularly when engaging with stimuli that enter PPS. Similarly, Coello et al. (2008) found that the location of object presentation was critical for participants' reaction times whilst performing a perceptual judgement task and a control task. Participants received transcranial magnetic stimulation (TMS) pulses at a frequency aimed to inhibit cortical excitability to the left motor and premotor cortex after each pulse. As a form of control, the subjects also received TMS to the temporo-occipital area. The perceptual judgment task required participants to determine whether an object was reachable or not without interacting with the object physically. The results showed that TMS to the motor areas caused a reduction in reaction times in the reachability task and this was enhanced when the objects were within PPS. This not only demonstrates the involvement of motor areas in processing visual stimuli but also further highlights the effect of PPS boundary on response times. It also suggests the involvement of these areas in processing information that enters this boundary (Coello et al., 2008).

Kimura and Katayama (2023) were interested in whether an approaching stimulus is enough to trigger such spatial prediction, or if it is required to occur in PPS to do so. Visual stimuli consisted of three

LED lights placed between the two hands of the participants, who had their hands placed in front of them. One tactile stimulus was used on one of the hands. The LEDs lit in a sequence towards the hand which received subsequent tactile stimulation to mimic an approach. Conversely, one LED flashed closest to whichever hand received the tactile stimulation. Subjects were required to respond when they felt the tactile stimulation. EEG recordings were taken throughout the task. The findings showed that activity in the somatosensory cortex was suppressed before the onset of the tactile stimulation, and this suppression was higher in the approaching condition compared to the near. Kimura and Katayama (2023) concluded that approaching visual stimuli improves the ability to predict and process a subsequent tactile stimulus better than static visual stimuli within PPS. This suggests that visual stimuli presented in PPS may have a predictive function, which aids in anticipating future tactile events, as well as acting as a defence mechanism (Kimura & Katayama, 2023). This extends our understanding of attentional processing within PPS.

Embodied processing in PPS has been supported by fMRI studies, with higher activation in the primary somatosensory when touch is presented on or close to the hand (Schaefer et al., 2012; Ladavas & Farne, 2004). Higher activation in the lateral occipital complex and ventral premotor cortex, when a stimulus approaches a subject's hand compared to when it's far away, was also seen. To confirm this, further neuroimaging studies have been used to measure the neural underpinnings of this process. EEG data has supported the activity in the somatosensory cortex when visuo-tactile stimuli have been presented in PPS, providing electrophysiological SEP markers of PPS processing (Deschrijver et al., 2016). When attention was focused on multisensory stimuli, the P100 and N140 were amplified and influenced by self-directed spatial attention, showing the influence of goal-directed attention at different distances from the body (Deschrijver et al., 2016).

Behaviourally, humans respond to touch on the body faster when paired with visual or auditory stimuli, as shown by a crossmodal congruency task (Serino, 2019). In this task, participants had to identify whether a vibrating touch was felt on their thumb (lower position) or index finger (upper position) while ignoring visual cues that may have appeared at the same or different heights. A cross-congruency effect was found, showing faster RTs when the tactile and visual targets were presented at the same elevation, and this effect was strengthened when the visual cues were presented closer to the hand (Serino, 2019). Faster responses were also shown when a tactile target was paired with auditory stimuli close to the hand compared to a sound far from the hand (Serino, 2019). This builds upon the earlier evidence of congruency effects in the near space, in which an enhanced P300 component was found contralaterally for congruent visuo-tactile stimuli on both hands, demonstrating the lateralisation of these effects (Longo et al., 2012). Furthermore, faster RTs and enhanced ERPs over the somatosensory cortex when visuo-tactile stimuli were presented in this space have been found (Sambo & Forster, 2009; Longo et al., 2012). This activity over the somatosensory cortex was only present at the N140 component and showed enhanced negativity for tactile stimuli in the attended areas (Sambo & Forster, 2009). The authors also highlighted an enhancement of the P100 in the presentation of congruent visual and tactile stimuli.

Research on PPS typically uses a pairing between visual or auditory stimuli with tactile stimulation to investigate multisensory integration in the brain. However, Noel et al. (2019) suggested a flaw in such methods. It is unclear whether PPS is a special area for processing multiple sensory inputs beyond its known role in processing touch. Most studies on PPS have looked at how senses like hearing or vision are combined with touch detection. These studies have shown that people are better at detecting touch when sounds or visuals are close to the body, suggesting a PPS representation (Noel et al., 2019). However, as these external stimuli get closer, they may naturally integrate better as different sensory modalities may get involved as the stimuli come closer to the body, therefore triggering this engagement. This means traditional PPS studies might have been mixing up the effects of closeness to the body with the natural tendency for nearby stimuli to be increasingly integrated well (Noel et al., 2019). Noel et al. (2019) were interested in whether the distance between an observer and a stimulus affects multisensory and unisensory processing differently, without using tactile stimulation due to its known association with activity in the somatosensory cortex in PPS. They recorded neural data using high-density EEG whilst they presented visual, auditory, and audiovisual stimuli at different distances. The authors used the subject's reachability to define the PPS boundary. Participants completed an auditory, visual, and audiovisual oddball task and were told to respond only when a stimulus was presented for a long duration. Results showed a significant effect of distance but only in the multisensory condition (audiovisual) on EEG global field power, with greater differences within the boundaries of PPS. This highlighted the effect of distance on multisensory integration within near space compared to far space, even when removing stimulation of tactile receptors.

So far, evidence has shown that stimuli presented in PPS are attended to faster and show higher neural activation across the somatosensory cortex, suggesting a fixed PPS boundary. However, recent evidence has suggested that the PPS boundary may be plastic and dynamic. PPS plasticity may be a result of learning or practice, such as using a tool (Serino, 2019; Galigani et al., 2020). The idea of a dynamic PPS boundary suggests that its limits can change rapidly in response to changes in the environment (Clery et al., 2015). The extension of the PPS boundary has been explored in terms of its plasticity using a tool to do so (Serino, 2019; Galigani et al., 2020). This is due to the modulation of sensorimotor experiences with increased multisensory interactions between the tool and stimuli. Plasticity is believed to arise from synaptic alterations triggered by stimulation during multisensory interactions with the environment (Bertoni et al., 2021). In the macaque brain, the size of the visual and auditory receptive fields usually matches the size of the tactile receptive field, overlapping and extending varying distances from the body. In the ventral premotor cortex (vPMC), most neurons have tactile receptive fields on the arm, but some also cover the shoulder, upper trunk, or face (Serino, 2019). Therefore, actions involving the arm and hand in particular, influence cortical representations of the PPS (Clery et al., 2015). A similar system is found in humans. Galigani et al. (2020) conducted an audio-tactile interaction task in which participants held a tool while receiving tactile stimulation and simultaneously heard an auditory cue either near or far from the participant's hand (localised at the tip of the tool). Following the use of the tool, RTs were found to be similarly faster in the far condition as seen in the near condition, suggesting similar multisensory facilitation as in the near space. Therefore, using a tool in the far space resulted in the tool being incorporated into the body's schematic representation of the space around it, resulting in a remapping of the PPS boundary (Clery et al., 2015). It has been argued that it is not the passive use of perception of the tool being used but is instead the active use of that tool that results in the extension of the near-space boundary (Clery et al., 2015). Object ownership also impacts the PPS boundary when participants observe and execute a grasping task while facing another, showing an expansion of this boundary when the object is identified as their own compared to the other's (Bogdanova et al., 2021). This suggests that tools that are owned by an individual may be integrated into one's own PPS, similar to how tools are. Furthermore, it has been proposed that plasticity is influenced by the type of information ahead, such as visual, emotional, and social-cognitive information, with long-range top-down synchronisation systems adjusting the representation of PPS (Clery et al., 2015). Emotional and socially cognitive demanding tasks are thought to involve these systems, but future research is required to investigate this interaction (Coello & Cartaud, 2021). Understanding how the brain integrates external stimuli, such as tools, into our body schema is crucial for highlighting the factors that can influence the embodiment of interactions with objects and tools.

Overall, research on PPS has highlighted the involvement of the somatosensory cortex in processing information that enters this space, providing insight into how spatial cognition functions (Coello & Cartaud, 2021; Sambo & Forster, 2009). In particular, neural correlates and further neuroimaging studies have mapped a multimodal interaction, which has supported the early findings of a PPS neural circuit in macaque monkeys (Rizzolatti et al., 1981; Holmes & Spence, 2004). Evidence has shown that the somatosensory cortex is heavily involved in processing tactile and visual information, with increased activation when the PPS boundary is entered. This is due to the protective and defensive role of the PPS (Kimura & Katayama, 2023). The interaction between these varying stimuli and their effect on the PPS may help to construct a better understanding of how the brain processes spatial information and can provide future clinical applications. The use of EEG and other neuroimaging techniques, such as fMRI have allowed for direct measures of neural activity, however, it is important to emphasise the lack of realism in the past traditional pieces of research. The use of novel techniques, such as VR, may provide a stepping stone in overcoming these limitations but needs further exploration. Despite this, it is clear that spatial attention is a complex interplay that needs to be investigated further to uncover whether there is an overlap in these processes with social cognition due to the involvement of similar brain regions. However, it has also been suggested that this boundary may not always remain stable and can instead be modulated by tools and object ownership (Clery et al., 2015; Bogdanova et al., 2021). It can also adapt based on the emotions and presence of others. Therefore, exploring these effects may be of use in understanding how the brain of typical individuals integrates sensory information as well as how task-related and top-down instructions influence somatosensory processing specifically in PPS.

1.6 The Interaction between Social Cognition and PPS

The interaction between PPS and social cognition is a growing area of interest, suggesting that spatial attention adapts in response to social stimuli. Processing and understanding others' emotions is crucial for effective social interactions, requiring high-level social cognition. Recent research has highlighted that PPS can in fact be influenced by social contexts (Clery et al., 2015; Coello & Cartaud, 2021). For instance, PPS has been suggested to adjust in response to social interactions, with various studies exploring how the PPS boundary is maintained and modified by social versus non-social intrusions (Serino, 2019; Vieira et al., 2020). This evolving understanding reveals that the brain's defensive systems and spatial perception are intricately linked with social cognition. Coello and Cartaud (2021) suggested that there is an overlap in processing tactile and social stimuli in PPS in the somatosensory cortex. The brain visually represents the surrounding space based on its past interactions with the environment (Coello & Cartaud, 2021). When engaging with social cognition, these interactions may shrink PPS, highlighting the potential modulation of social interactions on PPS (Coello & Cartaud, 2021).

Research by Vieira et al. (2020) and Pellencin et al. (2018) demonstrated that intrusions in PPS, whether from social or non-social stimuli or moral or immoral avatars, impact neural and behavioural responses. Vieira et al. (2020) explored how the brain responds to intrusions in PPS, from both social and non-social stimuli. The researchers used fMRI to examine the neural activity associated when PPS boundaries are breached by either social (e.g., another person) or non-social (e.g., an object) intrusions. They identified specific neural correlates within the brain's defensive systems that are activated during these intrusions, highlighting the role of a PPS system in regulating interpersonal distance (Vieira et al., 2020). The results showed that intrusions in PPS from social stimuli elicited an increase in activation in the midbrain and premotor cortex (Vieira et al., 2020). Activity was also found in frontoparietal regions, that have been linked to PPS. Therefore, this showed that the brain's defensive systems are engaged not only in response to potential physical threats but also in social interactions, thereby playing a crucial role in social behaviour and personal space regulation (Vieira et al., 2020). Similarly, Bogdanova et al. (2021) confirmed that the presence of another person modulates the PPS boundary. The findings as mentioned earlier showed a reduction in the congruency effect of stimuli presented on the same side in the PPS being responded faster to is affected by the presence of another person (Bogdanova et al., 2021). However, this effect only stayed true when the other person was situated in the subjects' PPS and when that person was carrying out the same task. Interestingly, a similar effect was found by Tennegi et al. (2013) but only in the presence of another human, when comparing the effect of presence between a person and a mannequin, which showed only a shrinking of the PPS boundary in the presence of another person.

A similar observation was found when facing a moral person compared to an immoral person (Pellencin et al., 2018). Pellencin et al. (2018) set out an experimental method that was controlled, yet highly ecologically valid, due to the use of mixed reality, which brings features from the real world into the digital world. The researchers aimed to confirm whether the social perception of others induces a change in how people perceive their own PPS. Two experiments were conducted to test this in which participants were immersed in an augmented reality environment (which typically overlays digital information into a digital world) showing a pre-recorded video of another person sitting across from them in a corridor. This location was the same in which they were tested, hence the immersive feel. The first experiment required participants to respond to vibrotactile stimulation on their hands while ignoring virtual objects moving towards their faces from the location of the other person. These virtual objects were presented using a head-mounted display. The tactile stimuli were delivered at varying time delays, following the movement of the virtual object, meaning that the touch was sensed at different distances from the subjects' bodies. The second experiment was similar to the first except participants' social perception of another person was manipulated, in which they faced a moral or immoral person. Participants watched a video of a female target who held a completed questionnaire regarding 17 different types of behaviours, in which some immoral behaviours were listed. In the moral condition, the female target was shown to have rarely engaged in immoral behaviours, whereas in the immoral condition, the target was shown to engage in immoral behaviours frequently (Pellencin et al., 2018). Tactile RTs were significantly faster when the virtual object was in the participants' near space compared to the far space (Pellencin et al., 2018). It was found that participants' PPS extended further when facing a moral person compared to an immoral one, suggesting that positive social perceptions can enlarge PPS. This supported previous findings on the social modulation of PPS but extended them by showing this effect occurs even in initial encounters based on first impressions. Unlike earlier studies, participants did not interact directly with the person but were influenced merely by the information provided about their moral character. Additionally, the study used VR to measure PPS in a social context, highlighting the possibility of a controlled yet realistic experimental setup by leveraging the immersive aspect of VR. Overall, the findings not only highlighted that social perception shapes the multisensory representation of space but also added to the idea of embodiment in social cognition since the social influence on PPS was specific to interactions with people and did not affect the PPS when facing inanimate objects (Pellencin et al., 2018). These studies underscored the importance of integrating social factors into our understanding of the PPS due to the clear impact it may have on the boundary. By examining these interactions, valuable insights can be gained into how the brain navigates both spatial and social environments.

Bogdanova et al. (2021) suggested that the social world influences PPS and describes PPS as a preferred distance that we keep between us to avoid discomfort. The involvement of high-level social cognition within PPS has been found to impact neural and behavioural responses using point-light displays (PLDs; Perry et al., 2010). Perry et al. (2010) used PLDs to replicate human biological movement to demonstrate to participants, while all other aspects of the stimuli were removed. Participants saw the same stimuli under different conditions – they were asked to judge the gender of the stimuli, the emotional expression or the intention conveyed. EEG recordings were taken simultaneously while the different tasks were completed. The authors were specifically interested in oscillations in the Mu rhythms. Perry et al. (2010) found significantly greater Mu suppression when participants had to identify intention from the stimuli (whether it was approaching or retreating). This highlights the increased neural activity in sensorimotor areas when performing social cognitive tasks during the observation of biological movement. Perhaps this suppression could be linked to the brain attempting to identify whether the visual stimuli are entering the PPS. ERPs were also measured when participants attended to visual-tactile stimulation in their PPS, showing less negative N1 amplitude when a fearful face was presented in the near space in VR, specifically in their peripheral field (Ellena et al., 2021). This suggests a neural link showing the impact that social cognition has on the brain, specifically when trying to process emotional stimuli within the PPS. Similarly, Cartaud et al. (2018) found a significant increase in physiological responses (electrodermal activity) when an angry face was presented in the participant's PPS using point-light displays. The researchers found that the boundaries of the PPS decreased in the presence of a dangerous object, suggesting an impact of the type of visual stimulus on PPS boundaries, further alluding to PPS plasticity.

The effect of empathy on PPS has also been of interest (Gherri et al., 2022). Gherri et al. (2022) investigated the relationship between individuals' empathy levels and their PPS properties, measured by the crossmodal congruency effect (CCE). This measure was taken from the difference in reaction times during incongruent and congruent trials and can provide behavioural differences in the processing of visuo-tactile stimuli within different spaces (Gherri et al., 2022). Participants completed a Crossmodal Congruency Task (CCT) in which participants responded to tactile stimuli while visual distractors were presented at varying distances. The CCT was used to force the brain to respond to more than one stimulus source, therefore activating multimodal areas. Reaction times to the tactile stimuli were measured to investigate the effect of the visual distractors at different distances (near, middle, and far). The IRI (IRI; Davis, 1980) was used to measure trait empathy, which was then correlated against the performance scores on the CCT. The results showed that participants with higher scores on the IRI (IRI; Davis, 1980), therefore higher levels of empathy, showed a weaker CCE at the near and middle distances compared to at the far distance. There was also significantly less differentiation between the PPS and extra personal space (the space between themselves and the space of others) in those who scored higher for empathy concern. The authors suggested that this effect was due to the fact that higher empathy may allow people to socially interact with others better in the far space than those who have lower empathy scores. The current study extended previous findings by showing that higher empathetic concern (EC) also affects multisensory PPS, not just responses to threatening stimuli. The findings suggested that high empathy might enhance the ability to navigate social spaces and interactions by expanding the perceived boundary of one's own PPS. This could facilitate better understanding and interaction with others, reflecting an increased spatial sensitivity in social contexts. Gherri et al. (2022) identified an overlap in the mechanisms behind multisensory PPS and social PPS processing and highlighted the need to explore whether the spatial sensitivity found in those with higher EC is present for social PPS.

Ruggiero et al. (2017) found similar results when exploring whether the emotions and facial expressions of others influenced the perception of distance. The researchers were particularly interested in PPS as well as the interpersonal space, which they define as the space which increases or decreases in response to comfortable or uncomfortable social settings, sharing a commonality with PPS. Participants were put into an immersive environment using a head-mounted display (HMD) where virtual agents with happy, neutral, or angry facial expressions were presented. To test the effect of the different expressions on the PPS, participants were instructed to press a button on a device they held when they felt the virtual agent was within reaching distance. Similarly, to test the effect on the interpersonal distance, participants pressed the same button, but instead when they felt that the distance at which they began to feel uncomfortable. This was completed twice, once when the participants walked towards the stationary agent in the VR, and again when the participants stood still, and the agents walked towards them. The results revealed an effect of emotional facial expressions on both types of spaces. In PPS, the distance at which participants began to feel uncomfortable was significantly larger when facing an angry virtual agent, compared to a happy agent. However, this was only present in the passive condition, where they had to stay still. This highlights the protective purpose of PPS by acting as a safety margin, resulting in avoidant behaviour (Ruggiero et al., 2017). The authors proposed an embodied perspective of social cognition, highlighting the interplay between emotional processing, spatial perception and behaviour. Lu et al. (2023) further supported these findings using a very similar methodology, whilst also measuring electrophysiological data. Participants had to stop virtual agents from coming closer by pressing a button, however, in some trials, this button press would not result in the avatar stopping. Behavioural data was also collected, and it revealed faster RTs to a virtual agent with an angry body expression compared to the neutral avatar. However, this effect was found when the avatar was presented at a far distance, suggesting that seemingly threatening facial expressions are attended to faster regardless of the distance. Furthermore, the angry avatar elicited a greater N170 ERP component and a smaller N3 than the neutral avatar. This suggests an enhancement of the N170 in emotional processing (Lu et al., 2023). The authors suggested that there is greater sensitivity to threatening stimuli, which occurs in the early stages of processing the avatar's presence. These studies contribute to the idea that the visual stimuli which require high-level social cognition impact behavioural and neural responses when presented within the PPS. It is important to highlight the use of immersive VR, which enhanced the validity of both studies due to the high realism in comparison to typical on-screen methods.

VR has been used to explore responses to stimuli in PPS, as shown by the previous studies. Fossataro et al. (2020) used immersive VR (IVR) to present a 3D model of participants' hands whilst simultaneously feeling small taps on either the congruent or incongruent hand that they saw a virtual LED light. Participants were instructed to respond only to the tactile stimuli, which either appeared near to or far from the hand receiving the tactile stimulation. Participants responded faster when the visual stimuli were closer to the hand receiving the stimulation in the congruent condition compared to the far, incongruent hand. The use of IVR allowed the authors to dissociate vision and proprioception by presenting the 3D models in different or the same positions as the participants' real hands. This study demonstrated how the brain integrates tactile and visual information to maintain an accurate representation of objects in the PPS, showing the impact of different spatial contexts on the perception of touch. This adds to the theory that tactile stimuli within the near space are attended to quicker than when further away, especially when coming from the same space as the visual stimuli. Additionally, VR has clear benefits in easily manipulating visual stimuli, therefore providing a solution to the issue of artificial paradigms. It allows researchers to create controlled yet immersive and realistic environments where tactile stimuli can be precisely manipulated and presented to participants. However, it is important to explore how VR can be best used in conjunction with neuroimaging measures to ensure accurate results.

1.7 A Note on the Use of Virtual Reality in Cognitive Neuroscience Research

Head-mounted VR is technology that can act as an interface between a person and a simulated environment with which the user can interact with (Li et al., 2020; Gibbs et al., 2022). Since its creation, VR has been used in various contexts, most commonly in gaming but also in training, therapy, education, and research (Cipresso et al., 2018). VR is increasingly being integrated into research due to its high realism, overcoming the unnaturalistic nature of on-screen methods in experimental designs (Parsons et al., 2017). As a result of this, there may be higher engagement due to the ability to rectify internal distractions (Li et al., 2020). Li et al. (2020) were interested in the level of selective attention (the ability to select what to attend to) and task performance in VR compared to two-dimensional (2D) displays. The authors conducted two experiments, testing behavioural and neural performance respectively, whilst participants completed a perceptual discrimination task. Participants in the VR condition engaged in attentional processes much faster than those who simply viewed the stimuli on 2D screens. On a neural level, heightened frontal activation was found when responding to the target in the VR environment. It was suggested that there is enhanced attention in the VR environment compared to 2D screen methods due to enhanced visuospatial sensory inputs resulting in higher corticothalamic activity (Li et al., 2020). This area of the brain is critical for enhancing the transmission of sensory signals from the eyes to the cortex (Osborne-Crowley, 2020). In social cognition, social stimuli in 2D videos or programmed formats are not equivalent to experiencing real-life social situations, raising questions regarding the real-world applications of existing research relying on such methods (Osborne-Crowley, 2020). This highlights the importance of reaching as high ecological validity as possible in social cognition research. However, combining VR and EEG may be thought to pose some issues regarding the quality of EEG signals. Hertweck et al. (2019) identified a theoretical gap in testing how true this is. The researchers used an Oculus Rift and HTC Vive Pro-two modern head-mounted displays and found sharp peaks in frequencies more than 50 Hz with the Oculus, which were not present when no HMD was used. Despite this, the quality remained largely unaffected in frequencies below 50 Hz compared to higher frequencies, and it was explained that these peaks were likely to be caused by the refresh rates of the devices. As a result, it is evident that the use of VR facilitates high ecological validity in social cognition research, whilst not affecting the quality of EEG measurements.

1.8 Ecological Validity in EEG and Social Cognition

Ecological validity refers to how well the findings of a study reflect real-world conditions (Osborne-Crowley, 2020). Whilst EEG measures are useful in highlighting millisecond neural changes, a main issue that is common in social cognition research is the artificial set-up of traditional experimental designs, which results in low ecologically valid paradigms and, therefore, limits the findings' real-world applications. This is particularly concerning when investigating the interaction between the brain and the external world, highlighting a methodological gap in this research. These issues can be addressed by combining traditional EEG measures with modern novel technologies like VR. For example, Ellena et al. (2021) used VR to present facial stimuli of neutral and fearful faces in near and far spaces. Their methodology provided a more realistic context for examining social cognition, thus enhancing the applicability of their findings to real-world scenarios. Comparing the approach of Ellena et al. (2021) with traditional EEG research, several key differences are evident in terms of ecological validity. Traditional EEG studies have relied on artificial stimuli, such as on-screen images or point-light displays, which have limitations in how realistic the biological movement can represent real human movement (Cartaud et al., 2018). In contrast, Ellena et al. (2021) employed stimuli presented in VR to better replicate naturalistic conditions. To address the methodological gap in EEG research, future research should look to adopt similar techniques to ensure ecological validity. This can be done by presenting stimuli of real human interactions in VR, which would further improve on the methodology used by Ellena et al. (2021), which used virtual avatars. By integrating more naturalistic stimuli, researchers can better understand how the brain interacts with the external world and ensure that the findings have real-world implications.

1.9 Rationale and Objectives

Understanding how the brain processes touch in different spatial contexts during social engagement is vital for unravelling the underlying mechanisms of social cognition and exploring embodied cognition in the brain. EEG measures offer valuable insights into neural activity during these interactions. ERP components such as the P100 and N140 reflect activity in the somatosensory cortex during touch and have been associated with processing multisensory information, particularly in the PPS, which have led to more pronounced early ERPs (Longo et al., 2012; Jones & Forster, 2013; Deschrijver et al., 2016). These components, along with the P45 and N80, have also reflected tactile and visual processing (Jones & Forster, 2013). EEG's high temporal resolution allows for millisecond changes in neural activity to be measured, highlighting a vital benefit of using this technique in attempting to measure the effect of task and distance on the brain, specifically the somatosensory areas (Ku et al., 2007; Peled-Avron & Woolley, 2022). This region is crucial for integrating tactile, visual, and proprioceptive stimuli to construct a representative model of the body's interactions with the external world (Gallese & Ebisch, 2013; Peled-Avron & Woolley, 2022). Moreover, theories of embodied cognition have suggested that inferring the sensations and emotions of others and interpreting spatial information involves a similar neural processing mechanism (Gallese & Ebisch, 2013; Peled-Avron & Woolley, 2022). This supports the idea that embodied experiences are critical for the cognitive processes of everyday social interactions (Wicker et al., 2003; Sel et al., 2020). For example, Mu rhythm suppression in EEG studies has been identified during the observation of social touch, indicating the activation of the sensorimotor areas in understanding the actions of others (Sel et al., 2020; Peled-Avron & Woolley, 2022; Perry et al., 2010).

PPS is essential for integrating multisensory information and modulating attention based on the proximity of stimuli to the body (Sambo & Forster, 2009; Kimura & Katayama, 2023). Additionally, the PPS has been suggested to be flexible and influenced by external factors, such as the presence of others. For example, processing social information has been shown to influence the boundaries of the PPS, affecting response times and neural activity during interactions with others (Pellencin et al., 2018; Bogdanova et al., 2021). Furthermore, VR has also been used to explore this interaction as it provides an immersive environment to study PPS dynamics and social interactions with high ecological validity (Fossataro et al., 2020; Li et al., 2020). It allows the manipulation of spatial contexts and social stimuli, overcoming the limitations of traditional experimental settings, and recent studies have shown its ability to preserve EEG signal quality (Hertweck et al., 2019; Osborne-Crowley, 2020).

This research aimed to add to the understanding of how the brain integrates tactile and social information across spatial contexts, which could later inform on what deficits in these aspects may look like whilst integrating VR in a research-based context, highlighting its usefulness in clinical and educational settings. Participants were immersed in a VR environment where they received tactile stimuli on their hands while they observed emotional conversations between two actors, presented in the PPS and extra personal space. EEG was recorded to capture ERP responses to tactile stimuli across the different spatial and social contexts. The analysis of ERPs was tactile-locked, meaning the mean amplitude around a millisecond timeframe around the tactile event for the ERP components was calculated and included. These components were the P45, N80, P100, N140 (Jones & Forster, 2013). Social manipulation involved presenting either happy or angry conversations to the participants.

Based on this, the following hypotheses were proposed:

1. It was expected that there would be a difference in tactile ERPs when the visual stimuli were presented in PPS compared to when presented at a far distance.
2. It was also expected that there would be a difference in tactile ERPs when people engaged in a social task, compared to a perceptual task.
3. It was expected that there would be early P45/N80/P100 differences when processing spatial information, particularly when visual stimuli were presented in the PPS compared to in the extra personal space. However, later N140 differences were expected when engaging in social cognition while participants performed the social task.
4. It was expected that there would be an interaction effect in which there would be a significantly bigger difference in the ERPs in the social task presented in the PPS compared to the non-social task presented in the extra personal distance space.

2. ***Methods:***

2.1 Pre-registration

This study was preregistered on the Open Science Framework (OSF) website, which can be accessed at: https://osf.io/cphtj. This creates a publicly available research plan such as stating a rationale, hypotheses, methodology, data collection processes, and analysis plan. The aim of doing so was to ensure complete transparency and reproducibility of the study by providing these details in advance, preventing selective reporting and purposeful data fishing. Due to the novelty of the methodology used in this study, there were some gaps in the registration, however, as much detail as possible at the time was provided and no data was collected prior to this pre-registration. The data and materials for this study are available to access from the link provided.

2.2 Sample Rationale

A power analysis using G*power was conducted. Whilst G*power does not compute interaction effects, the design was flattened, and a comparison was assumed across 4 conditions. A medium effect size of f = 0.25, given that the smallest observable effect of interest was expected to have a meaningful impact on cognition. A power of 0.95, with a correlation of 0.5 among repeated measures, was assumed. The power analysis resulted in a sample size of 36.

2.3 Participants

This study received ethical approval from the Middlesex University Research Ethics Committee. A total of 42 participants were collected. After the data exclusion process, 6 participants were removed. This resulted in a final sample of 36 usable participants with 16 Males and 20 females, of which 33 were right-handed, 1 was ambidextrous and, 2 were left-handed assessed by self-report. They were aged between 18 and 58 with a mean (*M*) of 26.36 (Standard Deviation *(SD)* =8.32). Participants were recruited through Middlesex University by placing participation advertisements across the campus or were personal contacts. The sample excluded those with epilepsy, those who were pregnant, and those who were susceptible to motion sickness based on the safety guidelines of the Meta Quest Pro used. Each subject was given a £15 Amazon voucher in return for participation. All participants gave informed consent before the start of the experiment. (See **7. Appendix** for the participation adverts placed around campus).

2.4 Stimuli and Apparatus

Visual Stimuli

The visual stimuli consisted of eight 90-second video recordings of two actors conversing. These conversations were recorded at 0.95m and 3.45m from a 360-degree camera (Insta360 Pro 2). A total of 4 of the videos were therefore in the near space, and 4 in the far space. In each of the distances, 2 videos portrayed feelings of happiness and the other 2 portrayed anger. The videos were recorded in the same location and position where participants were seated during testing, with the set-up of the testing room identical to the recordings (See Fig.1 and Fig.2). Once the videos were recorded, the program instapro360-stitcher was used to stitch and render them, creating eight 360-degree monoscopic videos that could be viewed in VR. They were all muted and trimmed to the appropriate length. Each video was shown twice, one in which participants had to complete a social task and in the other, a perceptual task. The order of the videos was randomised using E-prime 3. Trained actors were used and given clear instructions prior to filming. Before each clip was filmed, they were told to portray either of two specific emotions: happiness or anger. They were also instructed to touch their faces minimally, frequently or very frequently, with no specific numbers required to maintain the naturalism of the recordings. Originally, the videos were approximately two minutes long and a total of 27 clips were taken. They were then reviewed and selected based on the quality of the video. The videos which portrayed the emotions the most clearly, with clear facial touches were chosen. The videos were then muted to limit auditory input, and the length of the video was cut down to 90 seconds. The length of the videos was chosen to ensure that the total length of the study was appropriate for enough trials to be used and not exceed 30 minutes, as longer than this could increase the likelihood of participants experiencing motion sickness or discomfort.

***Fig.1**. Still from the 360 videos that the participants viewed in the VR headset. The image shows a still from one of the videos in the near condition.*

Fig.2. *Still from the 360 videos that the participants viewed in the VR headset. The image shows one from the far condition.*

Virtual Reality

A Meta Quest Pro was used to present the visual stimuli. The 360-degree videos were transferred onto the headset and viewed on the Meta TV application. This allowed participants to select each video as instructed using the Meta Quest Pro controller. This also allowed participants to follow instructions given, such as selecting the video required.

Tactile stimulation

Tactile stimulation was presented using one tactor connected to a TactAmp. The tactor is a miniature electromagnetic solenoid-type stimulator, 18mm in diameter, which drove a flat probe magnet (approx. 2mm in diameter) up and down, creating the sensation of a tap. Participants placed their right index finger on the tactile stimulator, which sent 100ms taps with a random ISI between 2150 and 4150ms between taps. These occurred whilst they watched the videos. The TactAmp was connected to the PCs' parallel port, which was also connected to the EEG amplifier. Therefore, each output of the tactor signal was linked to the EEG signal. To mask the sound of the tactor, white noise was played in the background throughout the entirety of the experiment through two speakers located to the left of the participants.

Toronto Empathy Questionnaire (TEQ; Spreng et al., 2009)

This questionnaire was used to measure the participants' trait empathy and to assess whether there was a link between ERP amplitudes and their empathy scores. Participants were asked to rate on a Likert scale of 0-4 (where 0=never and 4=always), how frequently they think they feel or act in the ways described by a list of statements. Examples of these statements include "When someone else is feeling excited, I tend to get excited too" and "I am not really interested in how other people feel".

E-Prime v.3 (Psychology software tools)
This program was used to send tactile triggers to the EEG, to counterbalance the order in which the videos were shown to each participant, and to control the timing of the tactile stimuli.

2.3 Design and Procedure:

There were 16 blocks with 56 tactile stimuli delivered in each block per participant. Half of the blocks involved a social task, and the other half involved a perceptual task. In the social task, participants were instructed to watch the videos and to engage with two questions; "What emotions do you think the actors are feeling?" and "What do you think the actors were talking about?". These responses were made verbally after the end of the video and were taken note of. In the perceptual task, a similar instruction was given but were instead asked, "How many times did each of the actors touch their faces?". A separate number of face touch responses was provided for both the left and right actors at the end of the video, and the responses were taken note of.

Upon arrival, participants were given a brief outlining the participation process and informed consent was gained. The completion of the TEQ followed this. Participants were then given a demonstration on how to use the VR headset, such as how to set the boundary (a way for the headset to know where the user is in the space) and how to select and play the videos. This also allowed participants to opt out in case of experienced motion sickness or any potential discomfort felt. They were then prepared for the EEG. The VR headset was then placed on the participants' heads and their right index finger was placed onto a tactile stimulator (see Fig.3.), which sent randomised taps throughout the videos. To mask the sound of the tactile stimulator, white noise was played through two loudspeakers throughout the experiment. Each trial started with the video playing, which lasted 1m 30s each. I was prompted by E-Prime v.3 on what video to play, and the participant was instructed to select and play that video. The participants either engaged in a social or perceptual task whilst watching each video. They were also told to ignore the tactile taps. After the participants finished watching the video, they verbally gave their answers, and I noted them down on a Microsoft Word document. The average time that the experiment lasted was between 1 hour and 1 hour 30 minutes. Participants were allowed to take as many breaks as needed in between blocks.

Fig.3. *Image of the set-up that the participant was in throughout the experiment.*

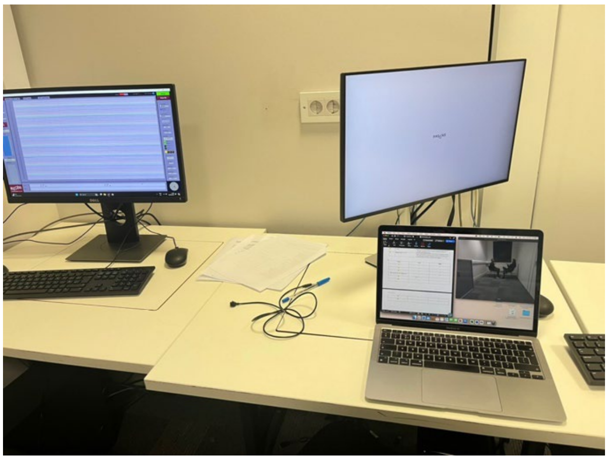

Fig.4. *Image of what I saw during the experiment, including the EEG recording, E-prime set-up, and the casting of the VR.*

2.6 Data exclusion criteria:

Following the visual inspection of the data, it was decided that a more conservative approach would result in higher-quality data, meaning I deviated from the pre-registered published plan on the exclusion criteria, which originally stated a threshold of 25 out of 56. The threshold used in this experiment was 20 out of 56, meaning if a participant's trial number reached below this, they were excluded from the data analysis and replaced. The main reason for exclusion was the number of artefacts identified in the EEG recording or if the participants were not properly engaged with the correct visual stimuli. One participant accidentally pressed a button on the controller, resulting in the required video restarting and a large amount of the taps given occurred when the participant was not engaged in the video, meaning their data was excluded. This happened on one occurrence. There were some instances in which participants accidentally paused the video but the time in which they were not fully engaged was less than 5 seconds, as noted during the experiment. Based on the artefact rejection during the EEG analysis, it was assumed that some of these trials would have been removed anyway, so entire datasets from these participants were not removed.

2.7 EEG Recording and Analyses:

EEG was recorded using a Biosemi Active Two system, and a 64-electrode EEG head cap, with a sample rate of 2058Hz. The common mode sense-driven right leg (CMS-DRL) was used as a reference. Data analysis was done on Brain Vision Analyser v2.1.1, Brain Products GmbH, and all EEG data was left in high resolution. filtering was applied with a low cutoff filter of 0.1v Hz and a high cutoff filter of 40Hz and a 50 Hz zero-phase notch filter. Channels were then checked manually for noise for each participant and interpolated if visible deviations were present throughout the recording. Only one channel for one participant was interpolated. The data was then re-referenced to the average of all 64 electrodes. Ocular artefacts were removed using ocular correction Independent ICA. ERPs were segmented from 100ms prior to the onset of the tactile stimulus to 800ms after. A 100ms pre-stimulus baseline correction was applied on each ERP. Artefact rejection was done on all channels across all participants and the exclusion of segments was carried out with amplitudes that surpassed +/- 100μv. A grand average was then calculated.

2.8 ERP Analysis:

The critical measured variable was the ERP components locked to the tactile stimulation, measuring sensorimotor activation. The mean amplitude from the following components was measured: P45, N80, P100, N140, Nd1, and Nd2. ERP mean amplitudes were computed for all measurement windows centred around the peak latencies (averaged across all conditions). The C3 and C4 electrodes were used to define the peaks of each ERP component contralaterally and ipsilaterally. For the P45 component, a positive peak was detected at 45ms with 10ms on either side of the peak (35-55ms). For the N80 component, a negative peak was found at 80ms with 10ms on either side (70-90ms). A positive peak was identified at 106ms for the P100 component, with 15ms on either side (91-121ms). For the N140 component, a negative peak was identified at 146ms with 20ms on either side (126-166ms). To investigate longer-latency effects of spatial attention, mean amplitudes were also computed between 170 and 350ms (Nd1) after tactile stimulation onset as well as from 350ms to 500ms (Nd2).

2.9 Statistical Analysis:

The analyses were completed using SPSS v27.0. A 2x2x2 repeated-measures ANOVA was conducted to test the hypotheses made. The factors were Distance (near vs far), Task (social vs perceptual), and Laterality (contralateral vs ipsilateral). The main effects were calculated, as well as interaction effects. If there was a significant three-way interaction effect, this was broken down into two 2x2 within-subjects ANOVAs. If there was a significant two-way interaction, pairwise comparisons were used to identify where this difference lay. If there were significant main effects, the means and standard deviations were used to investigate whether the two levels within the factors were significantly different from each other. This analysis was conducted for each component. Furthermore, exploratory analyses were conducted using the scores of the perceptual task. Each participant's score on how many face-touches they correctly counted was used to measure accuracy in the near and far distances. A paired samples t-test was conducted to infer whether there was a significant difference between the number of correct responses in the near distance compared to the far distance. Scores from the TEQ were used to investigate whether there was an effect of trait empathy on the averaged ERP amplitudes. To do so, the median was calculated from the distribution. The scores of the participants were then taken from either side of the median to form two groups. This was then used to run a 2x2x2x2 mixed-subjects ANOVA.

3. **Results**

The P45, N80, P100, and N140 components, and later latency components such as the Nd1 and Nd2 are common tactile ERP components. This study investigated whether these were modulated by the type of task performed and the distance at which stimuli were presented. Early activity in the somatosensory cortex can be seen in the presence of these tactile ERPs (Jones & Forster, 2013). In the following, I conducted 2x2x2 repeated measures ANOVAs to test the effect of Laterality (contralateral vs ipsilateral), Task (social vs perceptual), and Distance (near vs far). Separate ANOVAs were conducted using mean amplitudes for each of the tactile-locked ERP components (as defined in the *2.8 ERP Analysis* section).

3.1.1 P45 Analysis:

There was a significant main effect of Distance, $F(1, 35) = 9.14$ $p = .005$, $\eta_p^2 = .21$. The P45 amplitude was significantly larger at a near distance ($M = .36$, $SD = .89$) than at a far distance ($M = .16$, $SD = .93$). There was also a significant main effect of Laterality, $F(1, 35) = 40.34$, $p < .001$, $\eta_p^2 = .54$. The P45 amplitude was significantly larger at the contralateral site (C3 electrode) ($M = .75$, $SD = .88$) compared to the ipsilateral site (C4 electrode) ($M = -.23$, $SD = .64$) (See **Fig.5.**). There were no further significant main, or interaction effects found (all F's < .04, all *p*'s > .070).

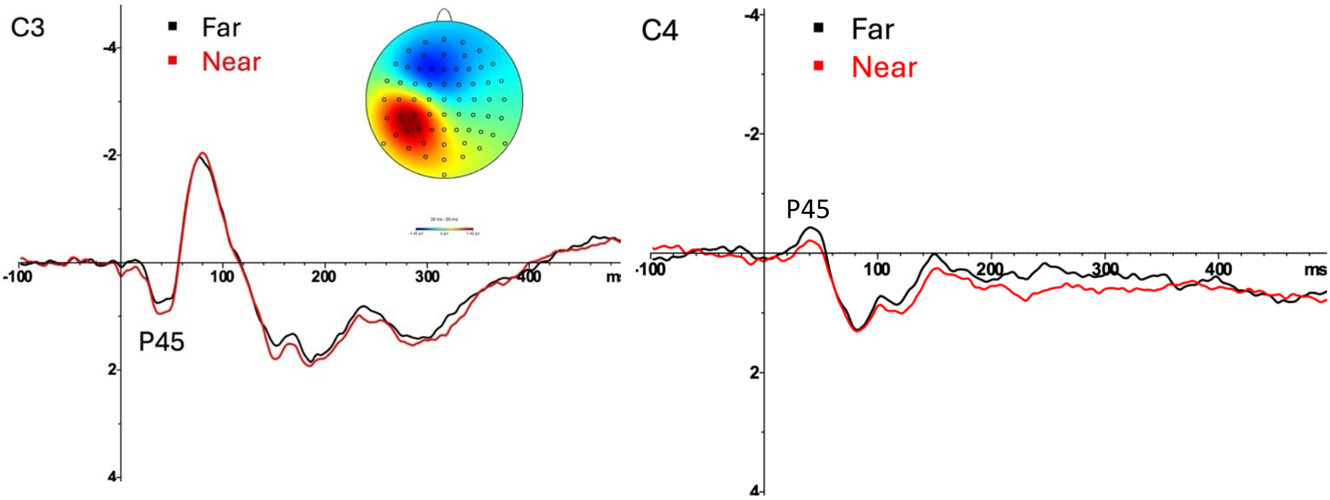

Fig.5. *Grand-averaged tactile-locked P45 amplitudes(μV) for both Distances in the far condition (black) and the near condition (red) taken from the contralateral site (C3 electrode) and ipsilateral (C4 electrode). Each ERP includes the average across Tasks completed in the relevant distances. The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites between the distances.*

3.1.2 N80 Analysis:

There was a significant main effect of Laterality $F(1, 35) = 120.18$, $p < .001$, $\eta_p^2 = .77$ (see **Fig.6.**). The N80 amplitude was significantly larger on the contralateral side (C3 electrode) ($M = -1.87$, $SD = 1.51$) compared to the ipsilateral side (C4 electrode) ($M = 1.18$, $SD = .81$). There were no further significant main effects or interaction effects (all F's < .02, all p's > .137).

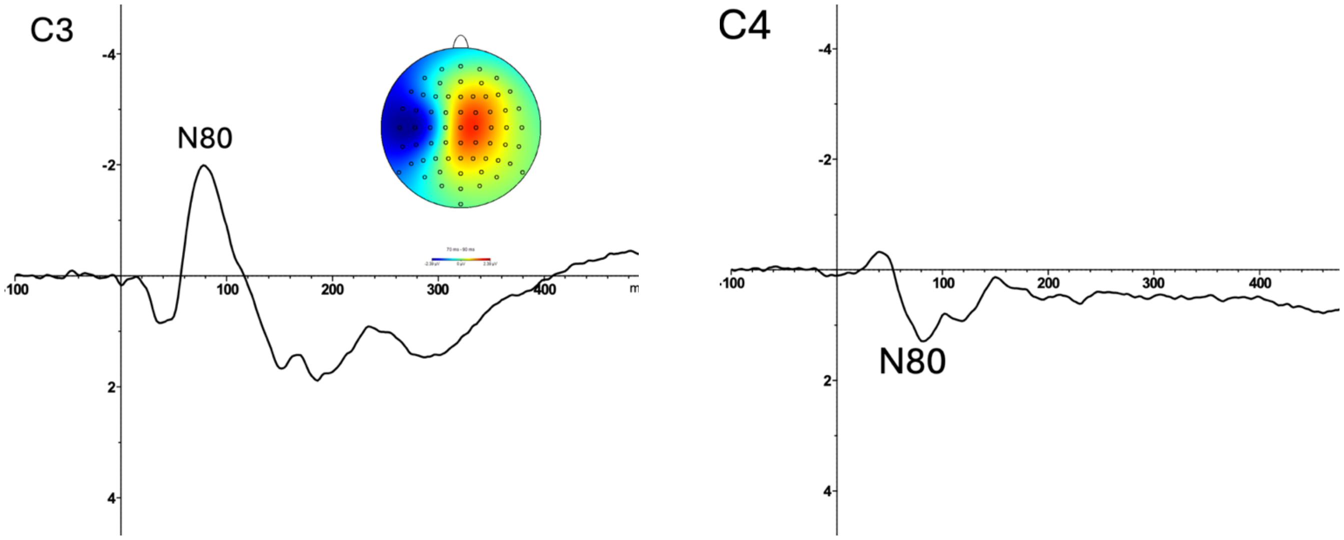

Fig.6. *Grand averaged tactile-locked N80 amplitude (µV) averaged across Distance and Task at the contralateral site (C3 electrode) and ipsilateral (C4 electrode). The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites.*

3.1.3 P100 Analysis:

There was a significant main effect of Laterality F(1,35) = 16.62, $p < .001$, $\eta_p^2 = .32$. There was a significantly larger mean P100 amplitude across the ipsilateral site (C4) ($M = .90$, $SD = .96$) than the contralateral site (C3) ($M = -.55$, $SD = 1.83$). No further significant main effects were observed (all F's < .07, all *p*'s >.271). There was a significant three-way interaction between Laterality, Task, and Distance F(1,35) = 4.98, $p =.032$, $\eta_p^2 = .13$. Therefore, the significant main effect of Laterality should be interpreted with caution as the three-way interaction suggests that the effect of Laterality on the mean P100 amplitude varies depending on the Task and Distance. To break down this interaction, two 2x2 repeated measures ANOVAs were performed separating the interactions between Task and Distance at the contralateral and ipsilateral sites. There were no significant interactions or main effects at the contralateral site (C3 electrode) (all F' < .02, all *p*'s > .319).

However, at the ipsilateral site (C4 electrode), there was a significant interaction between Task and Distance F(1,35) = 5.02, $p =.032$, $\eta_p^2 = .125$ (see **Fig.7.**). There were no significant main effects (all F's < .02, all *p*'s > .117). To understand the nature of this three-way interaction, pairwise comparisons with Bonferroni correction were conducted. In the perceptual task, the P100 amplitude was significantly larger in the near distance ($M = 1.11$, $SD = 1.00$) than in the far distance ($M = .72$, $SD = .96$), $p = .012$ (see **Fig.8.**). There was no significant difference between the Distances in the social task $p = .360$. In the near distance, there was no significant difference between the tasks, $p = .527$, as well as in the far distance $p = .405$. This indicates that the effect of Distance is modulated by the type of Task, with significant differences found in the perceptual task.

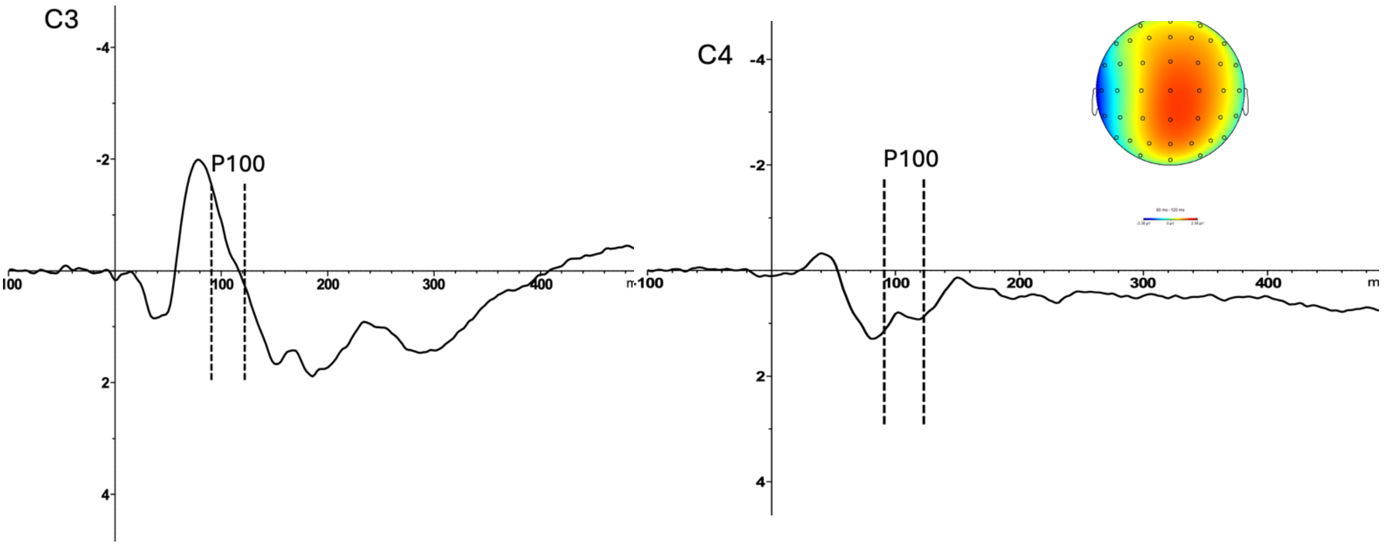

Fig.7. *Grand averaged tactile-locked P100 amplitude (µV) averaged across all conditions at the contralateral and ipsilateral sites (C3 and C4 electrodes). The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites.*

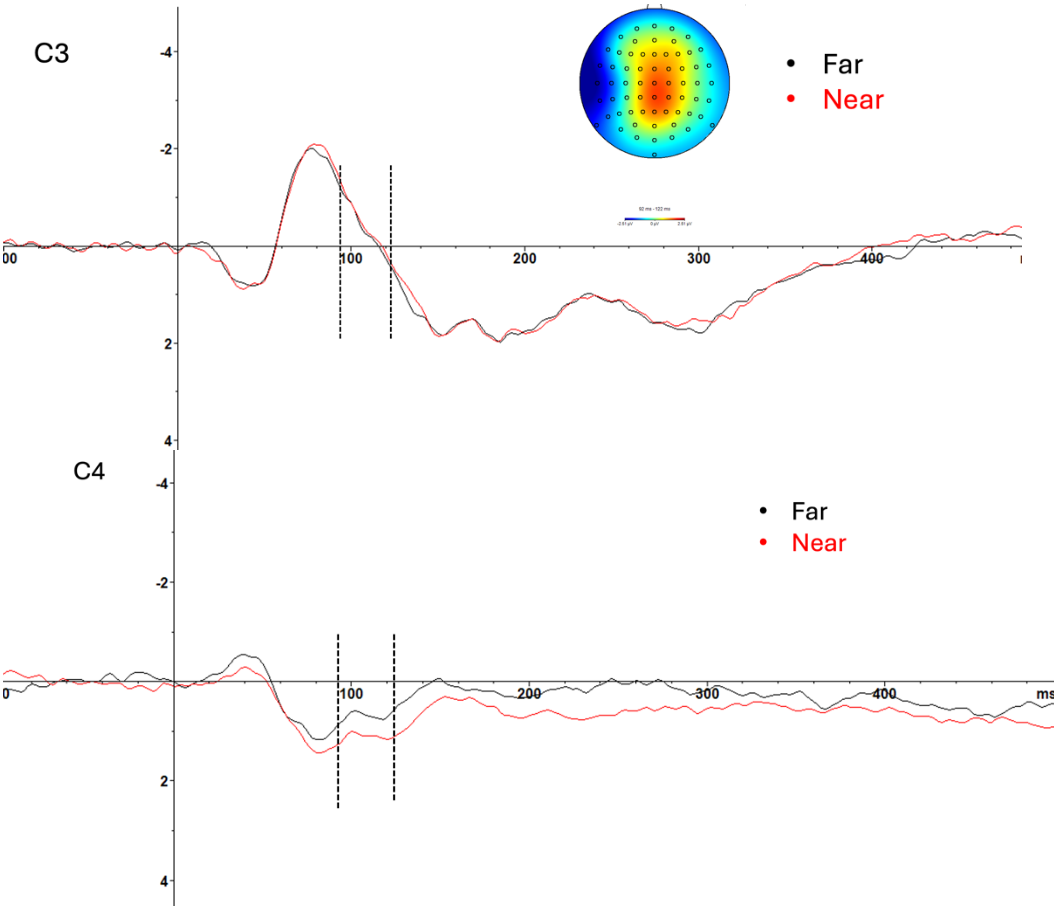

Fig.8. *Grand averaged tactile-locked P100 amplitude (µV) between the near and far distances in the perceptual task at the contralateral and ipsilateral sites (C3 and C4 electrodes). The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites between the two Distances in the perceptual task.*

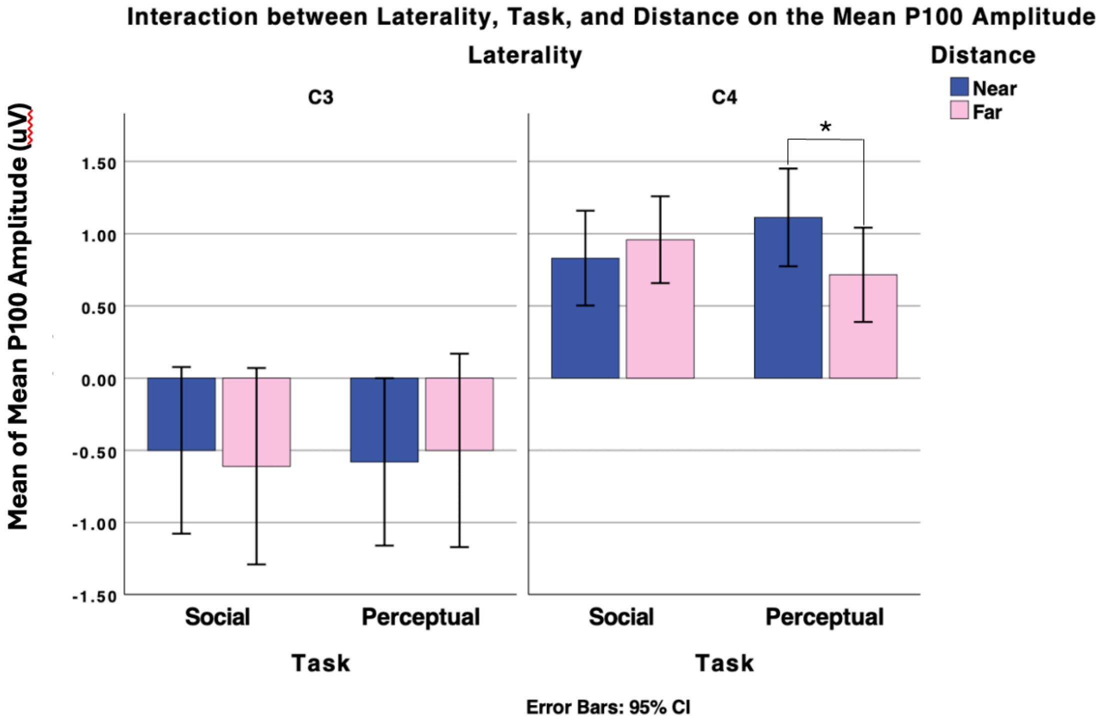

Fig.9. *A clustered bar graph showing the three-way interaction between Laterality (contralateral vs ipsilateral), Task (social vs perceptual), and Distance (near vs far) on the mean P100 amplitude (µV). Error bars represent the standard deviation from the mean. * p* = .012.

3.1.4 N140 Analysis:

There was a significant main effect of Laterality, F(1, 35) = 8.58, *p* = 0.006, η_p^2 = .20. There was a significantly larger N140 amplitude at the contralateral site (*M* = 1.27, *SD* = 1.68) than at the ipsilateral site (*M* = .38, *SD* = 1.20). There was also a significant main effect of Distance F(1,35)= 6.92, *p* = .013, η_p^2 = .165. There was a significantly larger mean N140 amplitude at the near distance (*M* = .91, *SD* = 1.40) compared to the far distance (*M* = .74, *SD* = 1.64). There was a significant three-way interaction between Laterality, Task, and Distance on the mean N140 amplitude, F(1, 35) = 6.45, *p* = .016, η_p^2 = .16 (see **Fig.12.**). This significant interaction suggests that the main effects of Laterality and Distance should be interpreted with caution. The interaction indicates that the effect of Laterality on the mean N140 amplitude varies depending on the Task and Distance, making it more relevant. Therefore, the main effect of Laterality or Distance cannot be discussed independently of the interaction effect. There was no main effect of the Task on the mean N140 amplitude F(1,35)= 3.78, *p* = .060, η_p^2 = .10. To further break down the three-way interaction identified, two 2x2 ANOVAs were performed at each Laterality site, contralateral (C3) and ipsilateral (C4), looking at the interaction between Task and Distance.

At the contralateral site, there was a significant main effect of Task, F(1, 35) = 9.50, *p* = .004, η_p^2 = .21. The mean N140 amplitude was significantly larger in the perceptual task (*M* = 1.41, *SD* = 1.65) than in the social task (*M* = 1.13, *SD* = 1.70), (see **Fig.10** and **Fig.12.**). There were no further significant main or interaction effects (all F's < 1.01, all *p*'s > .028). At the ipsilateral site, there was a significant main effect of Distance on the mean N140 amplitude, F(1, 35) = 4.40, *p* = .043, η_p^2 = .112. The mean N140 amplitude was significantly larger in the near condition (*M* = .50, *SD* = 1.18) than in the far condition (*M* = .27, *SD* = 1.21), (see **Fig.13.**). There were no further interactions or main effects (all F's < .12, *p*'s > .147).

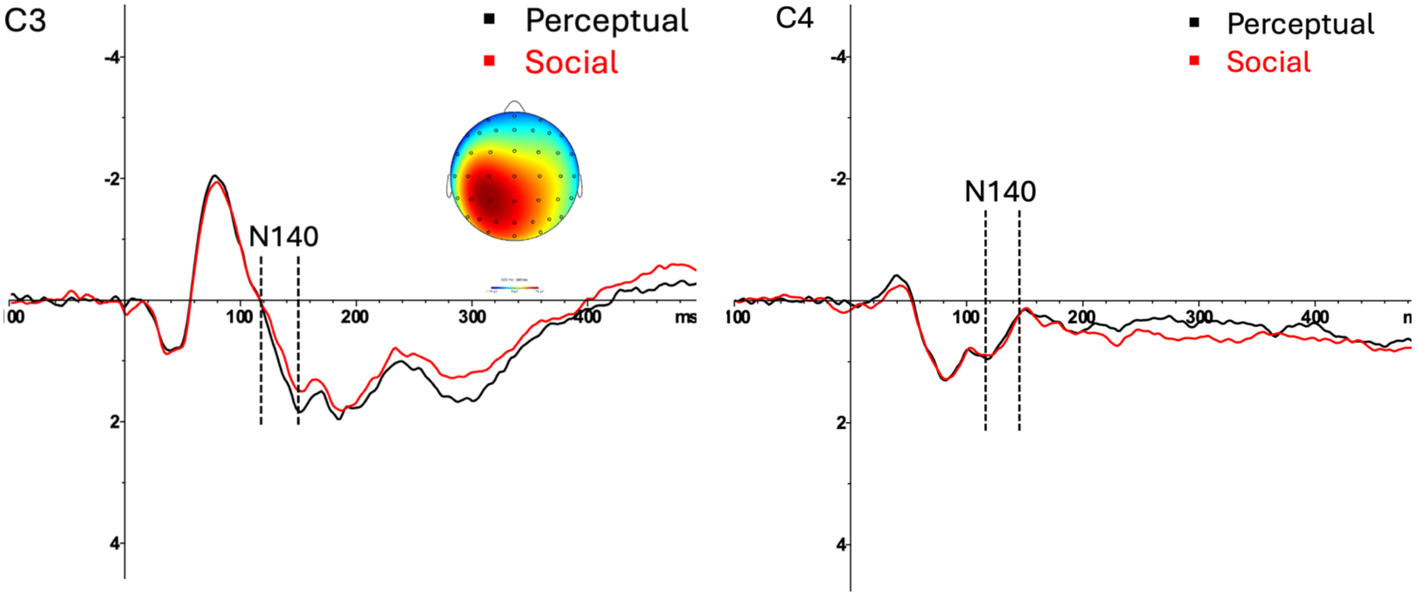

Fig.10. *Grand averaged tactile-locked N140 amplitude (µV) at the contralateral and ipsilateral sites for the social and perceptual tasks. The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites between Tasks.*

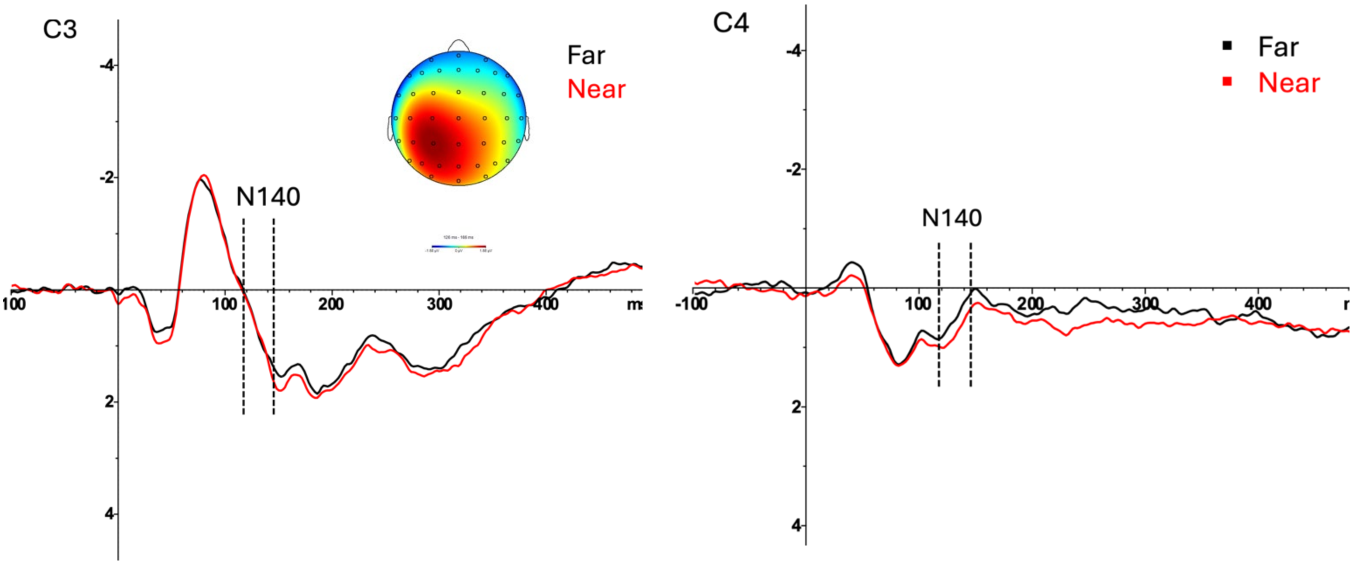

Fig.11. *Grand averaged tactile-locked N140 amplitude (µV) at the contralateral and ipsilateral sites for the near and far distances. The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites between Distances.*

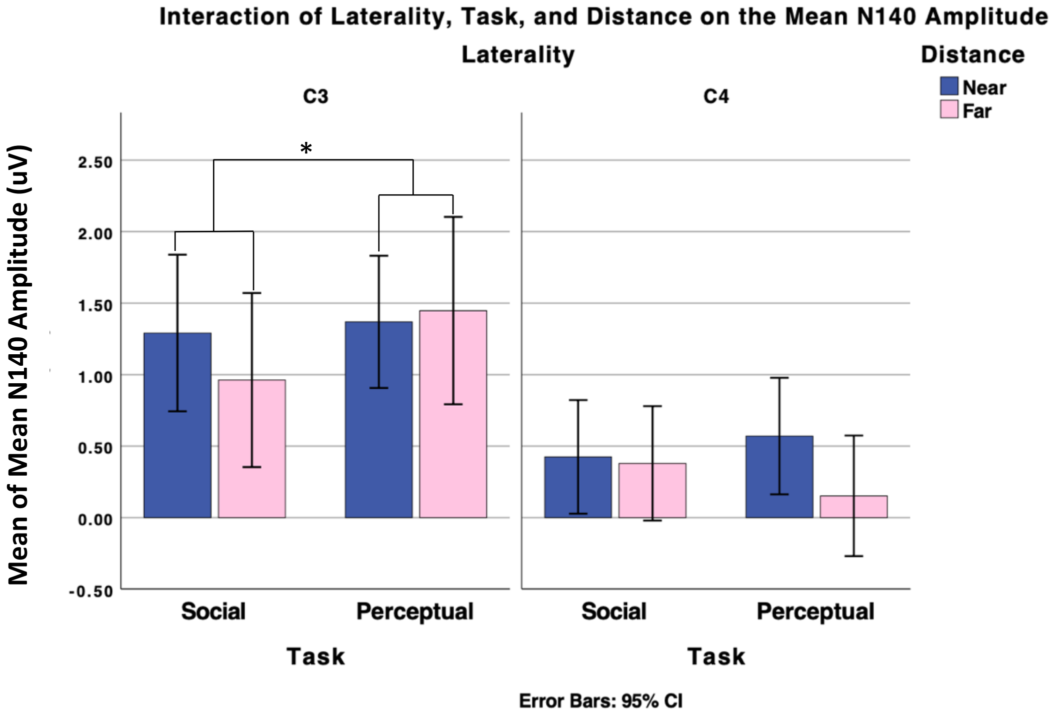

Fig.12. *A clustered bar graph showing the three-way interaction between Laterality (contralateral vs ipsilateral), Task (social vs perceptual), and Distance (near vs far) on the mean N140 amplitude (μV) The graph also shows the main effect of Task, F(1, 35) = 9.50, p = .004,* $\eta_p^2 = .21$*. The mean N140 amplitude was significantly larger in the perceptual task (M = 1.41, SD = 1.65) than in the social task (M = 1.13, SD = 1.70), *p = .004. Error bars represent the standard deviation from the mean.*

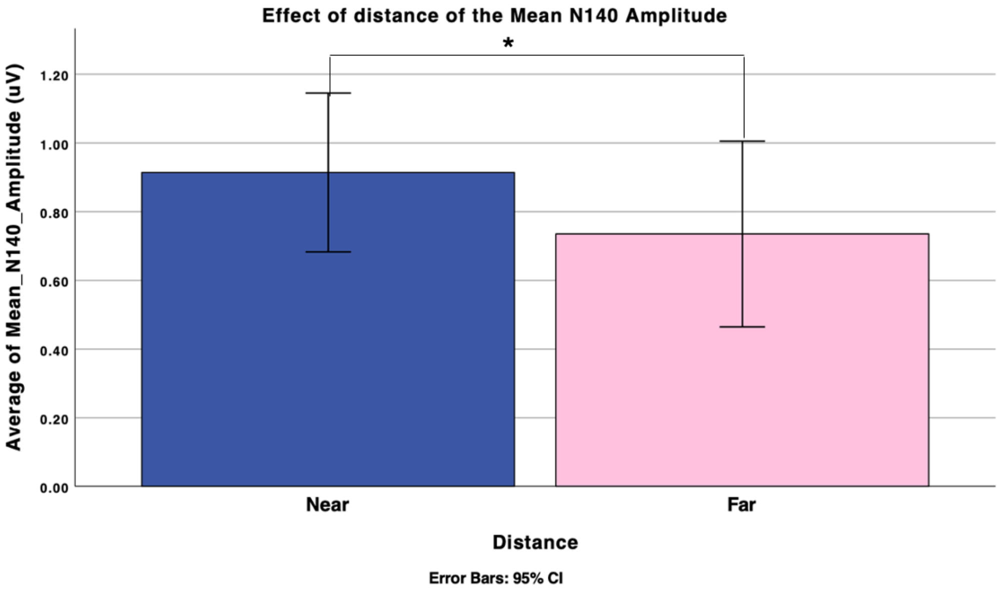

Fig.13. *A simple bar graph showing the main effect of the Distance at the ipsilateral site, showing a significantly larger Mean N140 amplitude (µV) in the near condition (M = .50, SD = 1.18) than in the far condition (M = .27, SD = 1.21), *p = .043. Error bars represent the standard deviation from the mean.*

3.1.5 Nd1 Analysis:

There was a significant main effect of Laterality, F(1,35) = 7.40 $p = 0.10$, $\eta_p^2 = .18$. The mean Nd1 amplitude was significantly larger at the contralateral site (C3) ($M = 1.29$, $SD = 1.43$) than at the ipsilateral site (C4) ($M = .47$, $SD = 1.40$). There was also a main effect of Distance F(1,35) = 7.00, $p = .012$, $\eta_p^2 = .17$ (see **Fig.16.**). The mean Nd1 amplitude was significantly larger at the near distance ($M = .98$, $SD = 1.33$) than at the far distance ($M = .79$, $SD = 1.36$). There was a significant interaction between Laterality and Task F(1,35) = 5.98, $p = .020$, $\eta_p^2 = .15$. This suggests that the main effect of Laterality should be interpreted with caution. The interaction indicates that the effect of Laterality on the Nd1 amplitude varies depending on the Task. Therefore, the main effect of Laterality cannot be discussed independently of the interaction effect. Finally, there was no significant main effect of the task on the mean Nd1 amplitude F(1,35)= .07, $p = .792$.

To understand the nature of the interaction between Laterality and the Task, corrected pairwise comparisons were conducted using Bonferroni correction. At the C3 electrode, there was a significantly larger mean Nd1 amplitude in the perceptual task ($M = 1.40$, $SD = 1.40$), compared to the social task ($M = 1.17$, $SD = 1.43$), $p = .010$ (see **Fig.16**.). There was no significant difference in the mean Nd1 amplitude between the tasks at the ipsilateral (C4) site, $p = .122$. In the perceptual task, there was a significantly larger mean Nd1 amplitude at the contralateral site (C3) ($M = 1.40$, $SD = 1.40$) than at the ipsilateral site (C4) ($M = .37$, $SD = 1.19$), $p = .003$ (see **Fig.16**.). In the social task, there was no significant difference in the mean Nd1 amplitude between the laterality sites (contralateral and ipsilateral), $p = .056$. There were no further interactions or main effects (all F's < .03, p's > .628).

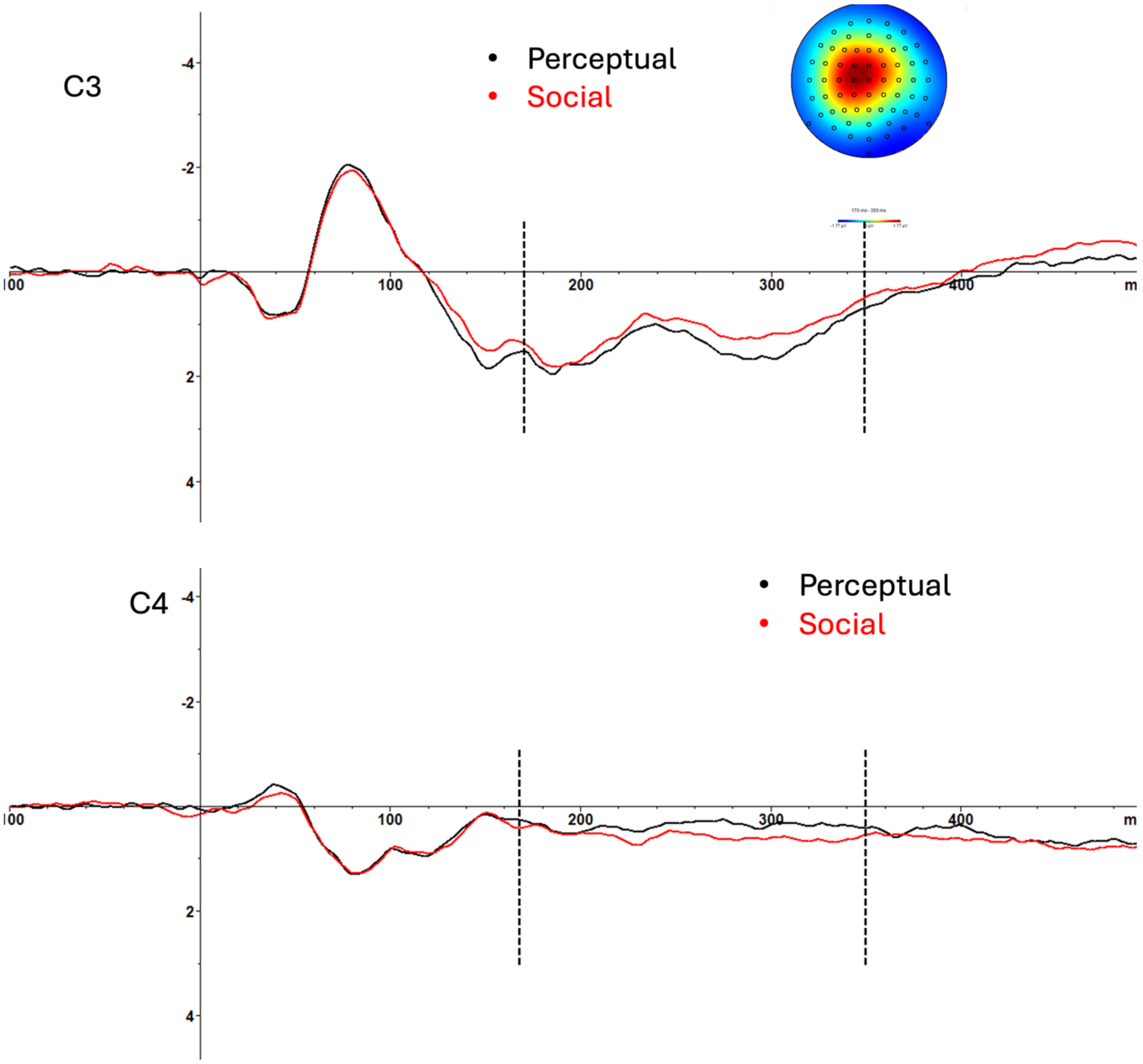

Fig.14. *Grand averaged tactile-locked Nd1 amplitude (μV) at the contralateral and ipsilateral sites between the social and perceptual Tasks. The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites between Tasks.*

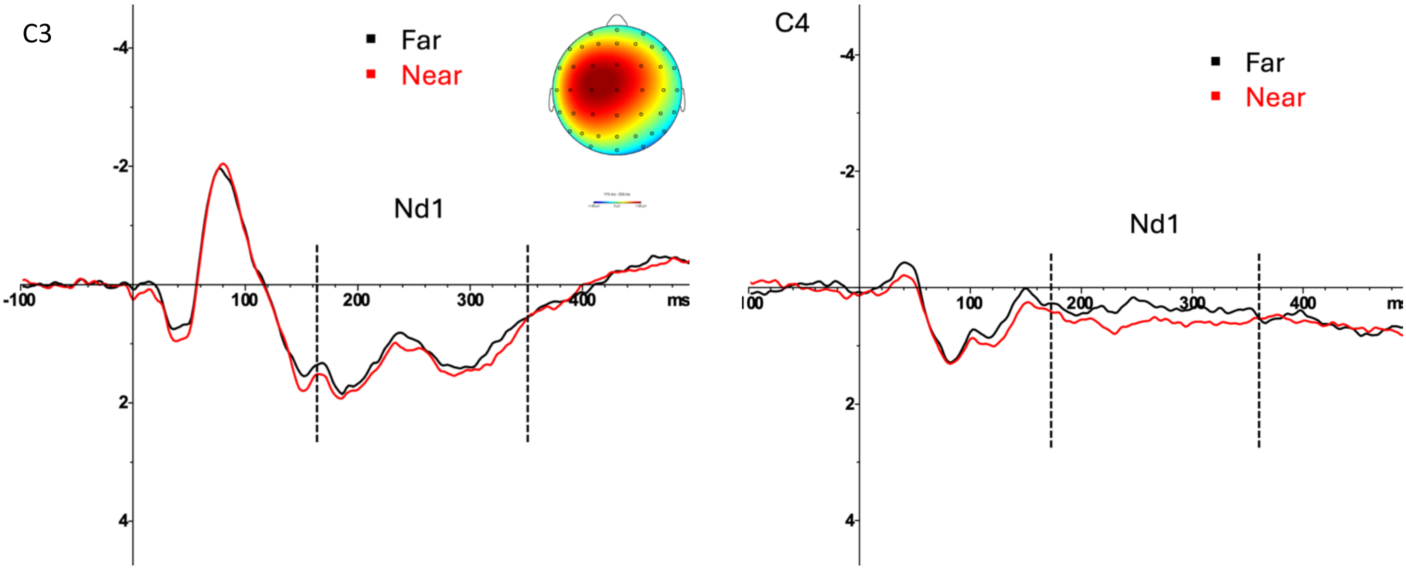

Fig.15. *Grand averaged tactile-locked Nd1 amplitude (μV) at the contralateral and ipsilateral site (C3 and C4 electrodes) across near and far distances. The topographical map represents the difference in neural activity observed at the contralateral and ipsilateral sites between Distances*

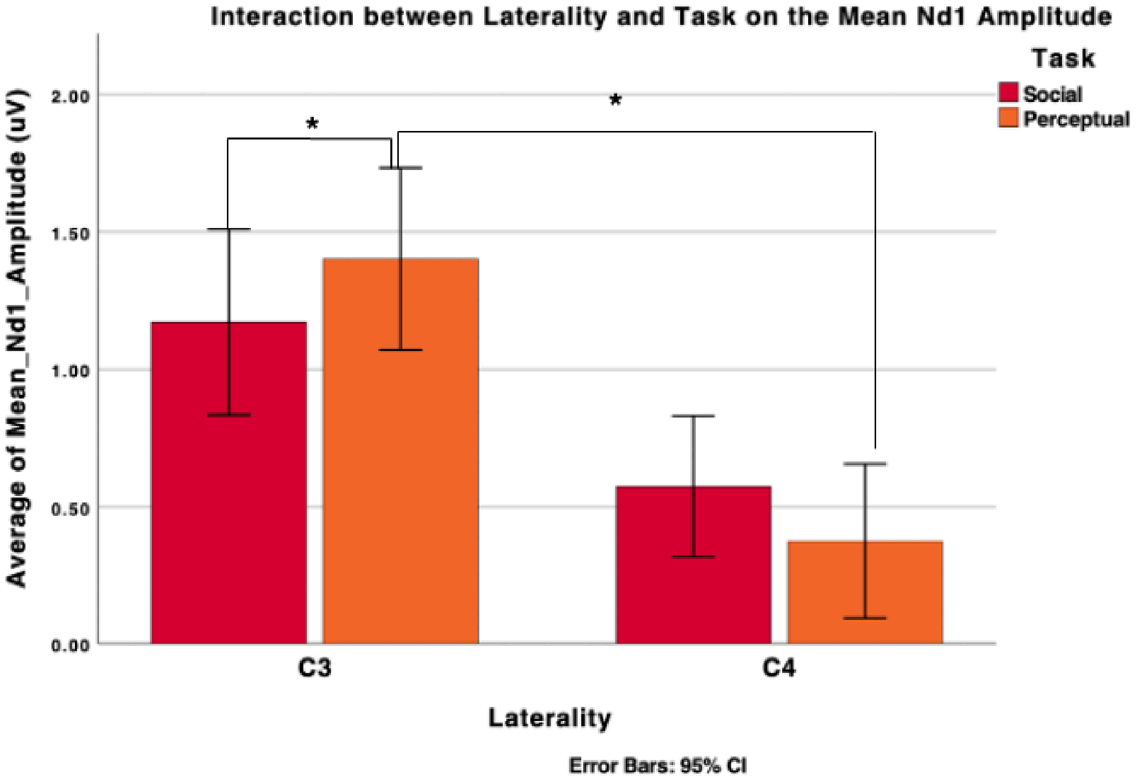

Fig.16. *A clustered bar graph showing a significantly larger mean Nd1 amplitude (µV) at the contralateral site (C3) (M = 1.40, SD = 1.40) than at the ipsilateral site (C4) (M = .37, SD =1.19), *p = .003 in the perceptual task. It also shows the significantly larger mean Nd1 amplitude at the contralateral site in the perceptual task (M = 1.40, SD = 1.40), compared to the social task (M = 1.17, SD = 1.43), *p = .010. Error bars represent the standard deviation from the mean.*

3.1.6 Nd2 Analysis:

There was a main effect of Laterality F(1,35)= 16.58, $p < .001$, $\eta_p^2 = .321$. There was a significantly larger mean Nd1 amplitude at the C4 electrode (*M* = .62, *SD* = .98) compared to the C3 electrode (*M* = -.06, *SD* = 1.03). No other significant main or interaction effects were found (all F's < .00, all *p*'s > .098).

3.1.7 Exploratory Analysis:

3.1.7a Accuracy of Perceptual Task:

Whilst keeping the score of the answers provided for both tasks was mainly to ensure that participants were fully engaged throughout the experiment, some behavioural data was extracted, which may be of interest in terms of the ERP findings above. In order to assess whether there was a significant difference between the scores in the near vs far conditions, a paired samples t-test was conducted. This showed that there was no significant difference in the scores between the near distance (*M* = 4.33, *SD* = 1.45) and the far distance (*M* = 1.89, *SD* = 1.51), *t*(35) = -1.81, *p* = .079.

Initially, the study's pre-registration stated an exclusion criterion based on the performance on the perceptual task, in which participants who scored below 60% would be excluded from the analysis from the exclusion criteria based on performance on the perceptual task mentioned in the pre-registration, which stated that anyone who scored below 60% would be removed from the analysis. However, after reviewing the performance data, the average score was 57.81%, meaning that the threshold of 60% was not met by a substantial number of participants. This may have been due to the difficulty of the task, and therefore, I deviated from this exclusion criteria. Please see the appendix for a table summary of the performance data.

3.1.7b TEQ and ERP components:

While the effect of empathy on ERP amplitudes was not a main hypothesis or area of interest, due to existing evidence on the effect of empathy on PPS and the link between empathy and social cognition, empathy scores may have been a confounding variable. Therefore, this potential effect was explored. In the following, I conducted a 2x2x2x2 mixed ANOVA to investigate whether there were significant differences between those who scored high and low on the TEQ on the averaged ERP amplitudes as part of the exploratory analysis. From the total TEQ scores, the median was calculated, which was then used to split the scores into two groups: high and low TEQ scores. These groups were then used as a between-subjects factor to conduct the mixed ANOVA. This process was repeated for each ERP component previously analysed.

TEQ and P45 Analysis:

There was a significant interaction between Distance and the TEQ scores F(1,34) = 5.61, $p = .024$, $\eta_p^2 = .14$. In the group that scored 43 or less, the mean P100 amplitude was larger at the near distance (*M* = .34, *SD* = .50) than at the far distance (*M* = -.01, *SD* = .43), $p < .001$. At the far distance, the mean P45 amplitude was greater in the group that scored more than 43 (*M* = .344, *SD* = .397) compared to those that scored less than 43 (*M* = -.01, *SD* = .43) $p = .019$. There were no other interaction effects (all F's < .08, all *p*'s > .052).

There was a significant interaction between distance and the TEQ scores F(1,34) = 6.67, $p = .014$, $\eta_p^2 = .164$. In the group that scored 43 or less, the mean P100 amplitude was larger at the near distance (*M* = .37, *SD* = .78) than at the far distance (*M* = .15, *SD* = .76), $p = .012$. There were no other interaction effects (all F's < .08, all *p*'s > .052).

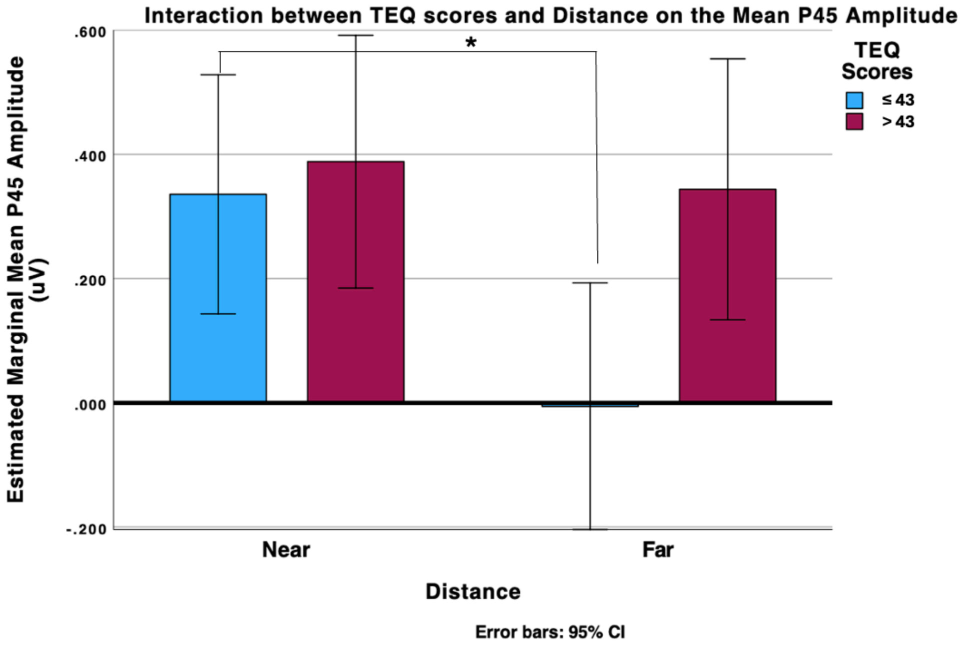

Fig.17. *A clustered bar graph showing the significantly larger estimated marginal mean of the P100 amplitude (µV) at the near distance (M = .34, SD = .50) compared to the far distance (M = -.01, SD = .43), *p < .001 in the group that scored 43 or less on the TEQ. Error bars represent the standard deviation from the mean.*

TEQ and P100 Analysis:

There was a significant interaction between distance and the TEQ scores F(1,34) = 6.67, $p = .014$, $\eta_p^2 = .164$. In the group that scored 43 or less, the mean P100 amplitude was larger at the near distance ($M = .37$, $SD = .78$) than at the far distance ($M = .15$, $SD = .76$), $p = .012$. There were no other interaction effects (all F's < .08, all p's > .052).

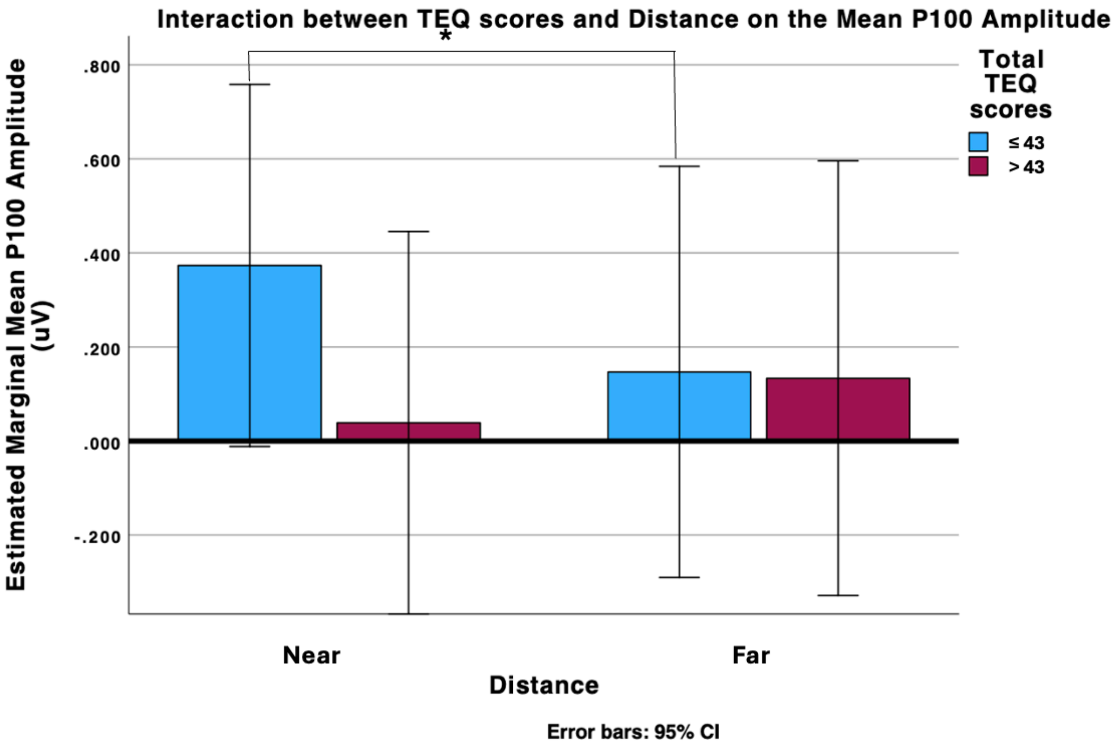

Fig.18. *A clustered bar graph showing the significantly larger estimated marginal mean of the P100 amplitude (µV) at the near distance (M = .37, SD = .78) than at the far distance (M = .15, SD = .76), *p = .012 in the group that scored 43 or less in the TEQ. Error bars represent the standard deviation from the mean.*

Other ERP components:

Across the N80, N140, Nd1, and Nd2, there were no significant interaction effects between the TEQ scores and Task, Distance, and Laterality (all F's < .01, all p's > .114).

In summary, the exploratory analysis revealed higher P45 and P100 ERP amplitudes for those in the low-scoring TEQ group in the near distance compared to those in the high-scoring group in the far distance.

4. **Discussion:**

4.1 Summary of Study:

The main aim of the present study was to explore how people process others when they are at different distances while focusing on social aspects compared to perceptual aspects and were specifically interested in how the somatosensory cortex is involved in this processing. ERPs were measured to investigate the neural underpinnings of this process in virtual reality. Specifically, the P45, N80, P100, N140, and longer latency effects (Nd1 and Nd2) were measured in order to understand how visuo-tactile stimuli are processed in PPS and extra personal space. By using VR, I also aimed to overcome the common limitations found in the previous literature regarding artificial experimental designs, limiting their applicability to real-life scenarios. This is particularly important as research into this area often relies on mimicking real-world interactions, in which on-screen methods tend to be a major limiting factor in doing so. To overcome this, I used a novel methodology by using VR to present visual stimuli, resulting in a more ecologically valid design. Participants watched several videos of two actors displaying either happiness or anger while engaging in a social or perceptual task. Throughout the presentation of the videos, tactile stimulation was given, and their neural activity was recorded to capture changes in the interested ERPs. This allowed for a more realistic assessment of how the brain integrates multisensory information, with a particular interest in how this occurs during social interactions in different spaces. The findings of the present study may offer a deeper understanding of the neural mechanisms underpinning social cognition, which can then be applied to clinical settings.

4.2 Summary of Results:

The findings revealed an early increase in neural activity to stimuli presented in PPS, shown by an increase in ERP amplitudes such as the P45 in the near distance. There was also a clear effect of task, in which the perceptual task led to a heightened neural response compared to the social task, evidenced by higher N140 and Nd1 amplitudes. Interaction effects revealed an increase in neural activity when stimuli were presented in the PPS boundary and during the perceptual task. This study also explored whether empathy levels, measured by the TEQ, affected ERP amplitudes. The results showed higher P45 and P100 amplitudes when stimuli were presented in the near distance for those with lower empathy scores compared to those with higher scores, suggesting a modulation effect of Empathy on neural activity during the processing of stimuli in the PPS boundary.

4.3 The Effect of Distance on Early Tactile ERPs

It was hypothesised that there would be an increase in ERPs in the near distance compared to the far distance. The present study identified an effect of distance, characterised by an increase in early tactile ERPs, specifically the P45 component when visual stimuli were presented in the near space. This finding underscored the heightened sensitivity and rapid processing of tactile stimuli when visual stimuli are presented within PPS, supporting the notion that the brain prioritises sensory information perceived in close proximity due to its potential involvement in recognising threats and preparing the body for immediate action and self-defence (Cartaud et al., 2018; Kimura & Katayama, 2023; Serino, 2019). It is important to note that this brain response was specific to tactile stimuli, which remained in the PPS boundary and did not move between near and far distances. The present findings supported the previous findings which suggested that stimuli within PPS elicit stronger neural responses in the somatosensory cortex, as indicated by the increased P45 amplitude at near distances (Kimura & Katayama, 2023). Specifically, past research has highlighted a consistent effect of distance on an increase in ERP amplitudes, especially in response to stimuli presented in PPS (Sambo & Forster, 2009; Longo et al., 2012). This increase has often been linked to the idea of the PPS boundary having a defensive role, in which stimuli which enter this space are attended to quicker and result in an increase in activity in the somatosensory cortex, which may also explain the similar findings in the present study (Sambo & Forster, 2009). Early activation in the somatosensory cortex during exogenous attention has been linked to elevated N80 and P100 ERP components, especially during the processing of tactile stimuli in the secondary somatosensory cortex (Jones & Forster, 2013). Furthermore, an enhancement of the P100 component has been observed when visual and tactile stimuli are presented simultaneously within the same spatial context (Serino, 2019). Additionally, the present findings may support the presence of a similar coding system in humans to that found in macaque monkeys, where this brain region is associated with a PPS neural network (Rizzolatti et al., 1981; Holmes & Spence, 2004). Teramoto and Kakuya (2015) suggested that the neurons found in this system fire proportionally to the distance at which visual stimuli are presented. Perhaps, there are similar neurons in the somatosensory cortex in humans which fire when the PPS boundary is violated (Teramoto & Kakuya, 2015). Therefore, the increased P45 amplitude in the near space identified in the current study may support this and could provide an extension of previous findings which outlined that when touch is presented close to the hand, there is a higher activation in the primary somatosensory cortex as found by Schaefer et al. (2012) and Ladavas and Farne (2004).

Interestingly, the effect of distance stayed consistent in the later ERP amplitudes, as seen by an enhanced Nd1 in the near condition compared to the far. The fact that this was seen in longer-latency effects may suggest a constant integration of multisensory information in the PPS, potentially linking back to a constant threat. Early ERP components, such as the P45, have been typically associated with initial sensory processing and have reflected early attentional processes that allow the brain to identify and prioritise potentially threatening stimuli (Luck, 2012). This finding specifically showed that enhanced somatosensory activity is present when visual stimuli are presented in near space and are likely linked to both early and late cognitive processes supporting the role of sensorimotor processing in multisensory PPS processing. In contrast, later components such as the Nd1, often reflect more sustained cognitive processes, such as integrating multisensory information over time (Luck, 2012). The presence of a distance effect across both early and later ERP components suggests that the brain (specifically the somatosensory cortex) does not only suggest there is a rapid and immediate response to stimuli in PPS but also continues to monitor and process this information over time to assess their level of threat. This supports the role of sensorimotor processing in multisensory integration in PPS, reflecting how the brain prioritises and evaluates stimuli that are near the body for immediate and appropriate responses.

While this was found in the P45 component, individual effects of distance were not evident in the N80 or the P100 components. It was expected that there would also be early N80 and P100 differences in the PPS compared to the far distance. This was based on the evidence of early somatosensory activity during tactile integration, particularly when stimuli were presented within the PPS boundary (Jones & Forster, 2012; Peled-Avron & Woolley, 2022). This suggests an almost immediate modulation of distance on somatosensory processing, particularly in integrating multisensory information presented in the PPS. This further adds to the extensive body of evidence suggesting the presence of a PPS neural circuit (Rizzolatti et al., 1981; Holmes & Spence, 2004). Overall, the enhanced P45 when stimuli were presented in PPS supports the early integration of multisensory information in the somatosensory cortex (Jones & Forster, 2013).

There was also an increase in the P45 and N80 at the contralateral site compared to the ipsilateral site. This suggests that there is a lateralised response in the processing of visuo-tactile stimuli, in which the activity in the primary somatosensory cortex (the region involved in processing tactile information) is more pronounced on the contralateral side (Cartaud et al., 2018; Kimura & Katayama, 2023; Serino, 2019). The findings also revealed no further effects of distance or task on the N80 amplitude, meaning that these did not elicit any task or stimuli-specific responses in the N80. Similarly, Jones and Forster (2013) found an absence of the N80 ERP correlate of early attentional selection during a dual task. This may explain the absence of a significant N80 ERP in the different distances and tasks. Even though participants were only completing a single task, there were multiple sensory inputs. Since task type and distance did not significantly impact the N80 amplitude, it suggests that the N80 component may have been relatively stable in its response to these factors. This might imply that the N80 is primarily influenced by basic sensory processing mechanisms rather than task demands or spatial context. However, I am tentative in these conclusions as I am drawing inferences from null findings.

These findings develop our understanding of sensory processing in the brain, especially regarding how tactile information is lateralised and suggest that visuo-tactile processing may be influenced by spatial proximity, as well as lateralisation.

4.4 The Integration of Spatial Proximity and Embodied Cognition

The findings showed that there was an interaction between Laterality, Task, and Distance at the P100 and N140 components, showing an effect of this interaction on these amplitudes. Similar to the findings by (Deschrijver et al., 2016), this suggests that the enhancement in the P100 and N140 components is modulated by the type of task and distance during multisensory processing. An overlap in sensorimotor activation has been suggested in social processing which occurs in PPS. This is due to the similar individual effects that space and engaging in social cognition have on the brain as well as its combined effect. Ruggiero et al. (2017) suggested an embodied perspective of social cognition, which proposes an interaction between emotional processing and spatial perception. Based on this potential interplay, it was expected that there would be a greater difference in ERPs in the social task presented in PPS compared to the perceptual task presented in the far distance. When this effect was broken down, an interaction between task and distance was found at the ipsilateral site in the P100 component. This was particularly pronounced in the perceptual task, which showed a larger P100 amplitude at the near distance, demonstrating a consistent effect of distance on neural activity. However, there was no effect of distance in the social task, which indicates that the perceptual task was the modulating factor, which contrasts my initial expectations.

It was initially expected, based on the theory that there is an increase in primary somatosensory activation when stimuli are presented close to the body, that engagement in a social task, such as trying to infer other people’s emotions, engages a similar mechanism, resulting in an increase in ERP amplitude (Wicker et al., 2003; Sel et al., 2020; Peled-Avron & Woolley, 2022; Perry et al., 2010). However, the unexpected findings of the current study may provide an alternative explanation. For instance, the P100 component has been shown to reflect early sensory processing, while later components (e.g., N140, P300) have been associated with higher-order cognitive functions (Jones & Forster, 2013). Therefore, the significant effect observed in the P100 amplitude for the perceptual task might indicate that the early stages of sensory processing are more sensitive to distance effects in simpler sensory processes, which do not require the processing of social cues.

Furthermore, cognitive load may have been a limiting factor. According to Lavie's (2005) perceptual load theory, tasks with higher perceptual demands require more attentional resources, leading to enhanced neural processing of relevant stimuli. In relation to the present study, the perceptual task may have required more focused attention and cognitive resources, resulting in larger P100 amplitudes. The presence of this effect in the near space may have been further enhanced due to a heightened attentional focus due to the proximity, aligning with the previously outlined findings of increased neural activity in the PPS. The higher perceptual load may have been a result of some practical limitations. The main limiting factor that could have directly resulted in a high perceptual load, and in turn an increase in the P100 amplitude during the perceptual task, was the difficulty. The perceptual task required participants to count the number of times each actor touched their faces, which posed several challenges. First, in some videos, the actors touched their faces multiple times very quickly, which could have made it difficult for participants to keep an accurate count. Despite the explanation of what constituted a face touch (i.e., the actor completely removing their hand from their face and then placing it back), participants might still have resorted to guessing due to confusion. Additionally, due to the set-up of the VR participants viewed the actors from a single angle (from the side), meaning that in the near condition (.95m from the subjects), participants had to turn their heads to capture movements from both actors physically. Overall, these explanations suggest that the larger P100 amplitude observed in the perceptual task at the near distance could have been a result of increased attentional demands and perceptual load, which poses an interesting question on the effect of perceptual load on spatial processing for future research.

The current findings, particularly the increased P100 amplitude when stimuli were presented in the near space, could provide evidence for how embodied cognition theories explain the brain's response to experiencing touch and how it integrates this in different spatial contexts. Embodied cognition theories propose that the brain integrates sensory information based on our body's interactions with the environment (Macrine & Fugate, 2020). In the present study, the enhanced P100 amplitudes observed during the perceptual task at the near distance could indicate that the spatial proximity of stimuli influences how tactile information is mapped and processed in social contexts. This is due to the fact that even during the perceptual task, the participants were still observing emotional conversations due to the use of the same videos in both tasks (Gallese & Ebisch, 2013; Peled-Avron & Woolley, 2022). This enhancement in the P100 component may reflect the embodied cognitive processes involved in integrating touch with spatial and social information. For example, the proximity of tactile stimuli in the near space might lead to more immediate and integrated sensory processing, as the brain's representation of the body's interaction with the environment becomes more important (Deschrijver et al., 2016). While the current study did not involve observing actual touch between actors and did not directly measure ERPs during observed touch and not observing touch, the findings are still relevant for understanding embodied cognition and could be used to argue a mirror neural circuit. However, this can only be speculative and interpretations on this should be made with caution due to the lack of direct investigation regarding this. Future research should further explore these findings by examining how different emotional contexts and spatial proximities affect ERP components like the P100 and specifically measure whether there are ERP differences in observed touch and no observed touch in these different spatial contexts. This could help elucidate the role of embodied cognition in shaping our sensory experiences and the integration of tactile and social information.

Another potential explanation for the enhanced neural activity during the perceptual task, particularly in the near space, is the previous plasticity effect of emotions on the PPS. Cartaud et al. (2018) suggested that the type of visual stimulus may affect PPS boundaries after displaying varying emotions using point-light displays. Perhaps, viewing and processing the emotions of the actors may have shrunk the PPS boundaries as previously suggested by Coello and Cartaud (2021). This may have caused participants to have a smaller PPS boundary, which was, therefore, not perceived as being disrupted, meaning that there may have not been any significant neural changes during the social task in the PPS. Furthermore, this study did not compare neural changes between the two emotions that were presented (happy and angry). Therefore, future research is needed to further explore the effect of engaging in emotional stimuli on PPS boundaries and neural activity, particularly utilising VR, in order to maintain the realism of the stimuli. ERP amplitude changes could also be measured between the different emotions as an extension of the present study, to explore if a more threatening emotion has any effect on the PPS boundary as well as neural activity. The fact that there were no significant differences in the P100 amplitude between the distances in the social task may suggest that engagement in emotional processing and social cognition affects neural activity irrespective of the distance in which stimuli are presented. However, the lack of a distinct increase in the P100 amplitude specifically related to the social task itself suggests that this task may not independently drive sensory processing to the same extent as the perceptual task.

A similar interaction was reflected in the N140. At the contralateral site, there was an individual effect of the task on the mean amplitude, which indicated an enlarged N140 during the perceptual task compared to the social task. Despite this, insights into how stimuli in different distances during social and perceptual tasks interact to influence neural responses can be useful in informing how deficits may present themselves, reinforcing the potential clinical implications. Interestingly, when this interaction was broken down, there was an increase in the N140 amplitude at the near distance compared to the far but at the ipsilateral site. Whilst the effect of distance was on the ipsilateral site compared to contralateral, which is typically expected, it shows the consistent heightened sensitivity to stimuli in the PPS. Furthermore, the novel methodological approach used with the combination of VR and EEG means that the findings of the current study may also be useful in the development of VR applications. Overall, the results contribute to a deeper understanding of the neural mechanisms underlying spatial perception and multisensory integration, reinforcing the importance of considering spatial context in studies of sensory processing and social cognition.

4.5 Exploratory Findings:

While the primary objective of the present study was not to explore differences in task performance across the PPS and extra personal space, existing literature suggests faster reaction times and task performance in the PPS (Teramoto & Kakuya, 2015). This insight could provide valuable information on how the brain processes information and handles cognitively demanding tasks at varying distances. However, while the results showed no significant differences in perceptual task performance between near and far spaces, this could be an interesting extension of the found effects of distance on neural activity. The lack of significant differences in performance may have been a result of the difficulty in the task. Head movement could have caused participants to miss some touches, further complicating accurate performance. To reduce the effects of the potential technological limitations, the task could have been simplified. For example, instead of counting multiple touches, participants could have been asked to identify specific, clearly defined touches, or the number of touches could have been reduced. Furthermore, ensuring that actors are within the participant's immediate field of view without requiring head movement could have been a further improvement. This could be done by increasing the distance at which the stimuli were presented, but ensuring they are still within the near space offering a clearer view without causing physical head movements. Moreover, even though brief training sessions before the actual experiment were incorporated, they were rather brief and did not actually give participants a chance to practice either of the tasks. Doing so could have helped participants become more familiar with the task requirements and reduced confusion about what constituted a face touch. By addressing these limitations and incorporating these suggestions, future studies can improve the reliability and validity of the findings, providing clearer insights into how the brain processes tactile and visual information in different spatial contexts.

4.6 Empathy:

The present findings suggested that empathy, as measured by the TEQ, did affect the perception and neural processing of stimuli within the PPS. Specifically, the study found notable differences in the P100 and P45 amplitudes between individuals with higher and lower empathy scores, indicating that empathy levels influence how tactile stimuli are processed in both near and far spatial contexts. The findings showed that participants with lower empathy scores (43 or less on the TEQ) exhibited a significantly larger P45 amplitude when stimuli were presented in the near distance compared to the far distance. This suggests that individuals with lower empathy may have a heightened neural responsiveness to stimuli within the PPS, potentially due to a more pronounced defensive mechanism. The same effect was found in the mean P100 amplitude. The ability to recognise and process other people's emotions is a key element of social cognition and is closely linked to empathy. The current findings are consistent with the previously established connection between empathy and activity in the primary somatosensory cortex, as well as the effect of trait empathy on the boundaries of the PPS (Schaefer et al., 2020). Specifically, it has been proposed that higher trait empathy enhances one's ability to navigate social spaces by expanding the PPS (Gherri et al., 2022). The findings from the present study indicated that low empathy levels may enhance the neural processing of stimuli even when they are near, suggesting a heightened sensitivity to social cues in this spatial context. Interestingly, this was not identified during the present study’s measure of social interaction, which may suggest an issue with the face validity of the stimuli presented. This supports the proposition that higher empathy may enhance sensitivity to social spaces, as suggested by Gherri et al. (2022). Additionally, those with lower empathy might be more vigilant and exhibit a heightened neural response to potential threats within their immediate environment. Notably, no other significant interaction effects were found, implying that the influence of empathy on ERP components is specifically pronounced in early processing (e.g., P100 in near space and P45 in far space) and not in later components. This broader attentional field may facilitate better social interactions and awareness of others in a more extensive context. Understanding the neural basis of how empathy influences spatial processing can inform therapeutic approaches for individuals with social cognition deficits. For instance, interventions could be designed to modulate PPS responses in conditions such as autism or social anxiety disorder, where social cognition may be impaired. Moreover, these findings can enhance VR applications by tailoring experiences that consider individual differences in empathy. It is important to highlight the effect of empathy on ERP amplitudes was explored as part of an exploratory analysis meaning these interpretations should be done with caution.

In summary, empathy levels may influence how the brain processes tactile stimuli in different spatial contexts, with distinct neural responses observed in PPS. These insights contribute to our understanding of the neural mechanisms underlying social cognition and the role of empathy in shaping perceptual and defensive processes within PPS. By leveraging this knowledge, future research and practical applications can better address the nuances of social cognition and improve outcomes for individuals with empathy-related challenges. Furthermore, as shown by previous studies, there is a clear space for the use of VR in research due to its high realism and ecological validity (Parsons et al., 2017). This compares to traditional on-screen methods, which raise a particular issue when trying to investigate social cognition. This area of research is highly dependent on mimicking real-life scenarios, such as showing stimuli of different facial expressions or avatars that simulate human interactions. Therefore, it comes into question how valid and applicable to real-life the findings of this research can be. Furthermore, the ability for VR to be used in combination with EEG, whilst maintaining a good signal, further highlights the advancement it could provide in future research, as well as in clinical settings. Understanding how task type affects neural processing in PPS can be extended into the designs of games. Game developers could purposely present stimuli in the near space to trigger immediate attention to a specific event. The current study may have also shown that the integration of tactile feedback could further evoke multisensory processing, which may be beneficial for user experience. In clinical settings, the present findings add to the literature on how a healthy brain responds to multisensory information, particularly in different spaces. Deficits in this may suggest neural issues in patients and could help to identify these cases. Additionally, these findings provide further evidence for the integration of VR into research. Despite the use of the VR headset on top of the EEG cap, the quality of the EEG signal remained relatively unaffected, which adds to the gap in the literature on the integration of both in research as suggested by Hertweck et al. (2019). This also supports the idea that these methods can lead to reliable and accurate findings.

4.7 Practical Limitations of the Study:

It is important to recognise some of the potential limitations of this study that may have influenced the findings and for future studies to improve on. While VR and EEG have been successfully utilised in previous research, their combination remains a novel method, bringing several practical concerns. In this study, participants had full control of the VR headset throughout the experiment, leading to instances where videos were accidentally paused mid-trial, meaning participants may have been distracted by this interruption. Although the participants who experienced several issues with the handling of the VR were removed, some instances went unnoticed for a few seconds, potentially affecting their engagement and the accuracy of the data. Another limitation impacting the results was how the tactile stimulation was given. The 'space' key was manually pressed to deliver the taps as soon as the video started, based on the participant’s VR display streamed to a laptop via a casting option. However, this may have resulted in a slight time lag due to the difference in frame rates. This could have resulted in vital millisecond differences between what the participant saw in the headset and what was displayed on the laptop. Therefore, the synchronisation between the tactile stimuli and visual presentation might not have been as precise as needed, especially due to the millisecond neural changes that can occur. Additionally, the study design required participants to watch the same videos for both social and perceptual tasks, potentially leading to task overlap. Participants might have engaged in the social task, trying to identify the emotions portrayed, while they were supposed to focus only on the perceptual task. This unintended overlap could have compromised the validity of some trials without my awareness.

Some practical improvements could be made in future studies to overcome these limitations. Implementing a more robust control system for the VR headset could prevent accidental pauses. For instance, disabling the pause function during trials or using a remote monitoring system to immediately identify and address any interruptions. Additionally, utilising a program that delivers tactile stimuli that are synchronised with video playbacks could eliminate human error. For example, triggering taps through a pre-programmed schedule or integrating software to ensure precise timing can improve accuracy. In order to reduce the impact of time lag and frame rate discrepancies, investing in higher-quality casting technology with minimal latency or using wired connections could ensure better synchronisation between the VR headset and the external display. In regard to the task, delineating tasks and providing explicit instructions could help to minimise overlap. For example, using distinct video sets for social and perceptual tasks could enhance focus and task adherence, as well as implementing brief questionnaires after each task to help verify whether participants adhered to the intended task. These would act as real-time monitoring tools to inform on task adherence and performance and would help me to identify and correct issues promptly. By addressing these practical concerns and incorporating these suggestions, future studies can enhance the reliability and validity of their findings, providing more accurate insights into the neural mechanisms underlying social cognition and spatial processing in VR environments.

4.8 A Note on the Constraints of Generality:

Simons et al. (2017) have highlighted the importance of specifying the target audience for which a study's findings are intended and what materials and procedures are necessary for replication. The authors suggested that successful replications of findings are more likely to be produced when the same target population from the original study is used. Making a constraint of generality (COG) statement allows other researchers to easily replicate the study, thereby increasing transparency (Simons et al., 2017). Regarding the present study, there is no reason for me to believe that the results have been influenced by other characteristics of the participants, materials, and or other historical or temporal factors (Simons et al., 2017). If the same procedure and materials are used, I expect that the results will be reproducible for the general population, as this study did not use a specific sample pool.

5. <u>Conclusion:</u>

In summary, the present study explored the neural response to touch whilst engaging in a social task compared to a perceptual task across the PPS and the extra personal space using VR. Research has previously outlined an overlap in the activity over the somatosensory cortex during the processing of spatial and social cues drawing a link to embodied cognition. Using VR, a novel methodological approach was used to overcome the artificial paradigms typically found in traditional studies on PPS and social cognition. Findings revealed an early heightened sensitivity to stimuli presented in the PPS, shown by an increase in the P45 amplitude when tactile stimulation was given during the presentation of visual stimuli in the PPS. The effect of distance seemed to interact with the type of task, revealed by N140 and longer-latency differences, namely in the Nd1. However, unlike what was initially proposed in which an increase in ERP amplitude was expected during the social task, there was an enhanced amplitude during the perceptual task compared to the social task, shown by an increase in the N140 amplitude during the perceptual task compared to the social task. This may have been due to the higher cognitive demand and load that the task placed on the somatosensory system. Alternatively, the present findings may put forward evidence for embodied processing of touch in social contexts. From the early effect of distance on mean ERP amplitudes, and a later effect of task, an interesting picture of how the brain processes information can be drawn. It can be suggested that there was an immediate response to the distance of stimuli first, especially when it was within the PPS boundary, reinforcing the concept of the PPS as a critical zone for heightened neural processing. The increased ERP amplitudes for near-space stimuli suggested a prioritisation of sensory information that is closer to the body, which could be linked to evolutionary survival mechanisms. The brain may then have engaged in the content of the stimuli. Future research is needed to explore whether this is unique to touch or if observation of any action within the PPS boundary can trigger this same mirror-like effect. Moreover, the findings highlighted the influence of empathy on the neural processing of distance, with lower empathy levels perhaps resulting in a heightened sensitivity to stimuli intruding on the PPS boundary. These insights into the neural underpinnings could have vital clinical implications by highlighting expected and typical neural processes of spatial cues. The use of VR offers further potential enhancements for VR applications, such as for game developers who could manipulate game environments to trigger a desired experience. It also provides evidence for the incorporation of VR with EEG to pave the way for more applicable and impactful research.

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7. Appendix:

Information sheet:

MIDDLESEX UNIVERSITY

Participant Information Sheet

Title of Project: How do neural responses to touch in peri-personal space (PPS) change during a social compared to a non-social task: measured using EEG and presented in a virtual reality environment?

Name of Researcher: Vanessa Sofia Amaral Lopes Simoes

Date:

SECTION 1

1. Invitation paragraph

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

2. What is the purpose of the study?

This study aims to bridge the methodological and theoretical gap by combining virtual reality (VR) and encephalography (EEG) to explore whether there are differences in neural responses between social and non-social cognitive processes in the different spaces around a person. Tactile stimulation will be used, in conjunction with VR and EEG, to investigate the neural responses to the types of tasks, in the different spaces.

3. Why have I been chosen?

It is important that we assess as many participants as possible, and you may have indicated that you are interested in taking part in this study. You have also been invited as you have no history of epilepsy, are over 18 years old, and are not pregnant.

4. Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep (and be asked to sign a consent form if your personal data will be processed). After having completed the study, it will not be possible to withdraw your individual data as your individual data will not be identifiable in any way, meaning the researcher will not know which data is yours.

5. What will I have to do?

You will only be required to visit the lab once. Upon arrival, you will be given a consent form to sign. You will then be given the chance to try the VR headset on for around 5 minutes to ensure you do not feel motion sick. The EEG capping-up will then begin, which will take approximately 30 minutes.

EEG cap-up process:

Electrodes will be placed on the surface of your scalp and an electrolyte gel will be used to ensure that there a good signal transmission is reached. This gel is water and salt-based and is non-irritating and does not stain. The researcher will measure your head using a measuring tape and then provide you with an electrode cap to wear on your head. Once the cap is on, the electrolyte gel will be added to your head using a blunt syringe (has no needle) by the researcher and this will only feel like a slightly cold sensation on the skin. The electrodes will then be 'clicked' into the cap, you will not feel any pain in this. The application of electrodes is completely pain-free, however, you will be able to feel the gel on your scalp. If at any point you feel discomfort, please let the researcher know immediately. The total time taken to prepare the EEG set-up should be no longer than 30 minutes.

Once complete, you will begin the experiment. You will be shown a series of clips through the VR headset whilst simultaneously being tapped on one of your index fingers using a small vibration. In some trials, you will be required to state what emotions are being displayed by the actors in the clips. In other trials, you will be asked to count how many times an actor raises their hand above their head. EEG data will be recorded throughout the experiment. The total time for the experiment to be complete will be around 1 hour and 30 minutes, including the time taken for the EEG capping. Once you have completed the experiment, the EEG cap will be removed, and you will be debriefed. You will then be given the opportunity to wash your hair.

Please note that in order to ensure quality assurance and equity this project may be selected for audit by a designated member of the committee. This means that the designated member can request to see signed consent forms. However, if this is the case your signed consent form will only be accessed by the designated auditor or member of the audit team.

6. Will I have to provide any bodily samples (i.e. blood/saliva/urine)?

No.

7. What are the possible disadvantages and risks of taking part?

The main disadvantage is the possibility of experiencing motion sickness from having the VR headset on. Therefore, you will be given breaks in between the experimental blocks. You may also experience slight discomfort while you are being capped up for the EEG as it can sometimes be a long process, but you will be allowed breaks throughout.

Appropriate risk assessments for all procedures have been conducted and will be followed throughout the duration of the study.

8. What are the possible benefits of taking part?

Participating in this study will not benefit you directly. The information we get from this study may help us to learn about how your brain responds to stimuli when it is close to you, compared to when it is further away. You will also be given a £15 Amazon voucher for taking part.

9. Data Protection and Confidentiality

Personal data is any data that can lead to the identification of a specific (living) person. It can be obviously identifiable data such as name or ID number but it can also be a combination of "innocent" data such as age, height/weight, wealth, job position, company, city, etc. that when combined can lead to the identification of a person. Processing of personal data is any activity that is carried out with personal data (including collecting, analysing, recording, etc). Personal data (e.g., your name, email address, voice or any data that can identify you) WILL NOT be processed by this study and your confidentiality will be protected.

10. What will happen to the results of the research study?

The results of the research study will be used as part of a Postgraduate dissertation. The results may also be presented at conferences or in journal articles. However, the data will only be used by members of the research team and at no point will your personal information or data be revealed.

11. Who has reviewed the study?

The study has received full ethical clearance from the Research ethics committee who reviewed the study. The committee is the Psychology Committee.

12. Contact for further information

If you require further information or have any questions, then please contact:

Researcher:
Vanessa Sofia Amaral Lopes Simoes (VA399@live.mdx.ac.uk)
Supervisors:
Dr Jonathan Silas
(j.e.silas@mdx.ac.uk)
65/Town Hall/HEN
Dr Alexander Jones (a.j.jones@mdx.ac.uk)
TG68/Town Hall/HEN
0208 411 6328
Dr Peter Passmore (p.passmore@mdx.ac.uk)
TG10/Town Hall/HEN
0208 411 6428

Consent form:

CONSENT STATEMENT

I have read and understood the participant information above and by answering questions in the questionnaire(s), I freely and voluntarily give my consent to participate in this project/study.

Thank you for agreeing to take part in this study. You (the participant) should keep this Participant Information sheet since it contains important information and the research team's contact details.

Version Number…

Participant Identification Number:

CONSENT FORM

Title of Project: How do neural responses to touch in peri-personal space (PPS) change during a social compared to a non-social task: measured using EEG and presented in a virtual reality environment?

Name of Researcher: Vanessa Sofia Amaral Lopes Simoes

Supervisor's name and email: Dr. Jonathan Silas (j.e.silas@mdx.ac.uk), Dr. Alexander Jones (a.j.jones@mdx.ac.uk), Dr Peter Passmore (p.passmore@mdx.ac.uk)

Please initial box

1. I confirm that I have read and understand the information sheet dated ....…… for the above study. I have had the opportunity to ask questions and have been given contact details for the researcher(s) ☐ 1

2. I understand that my participation is voluntary, the data collected during the research will not be identifiable, and I am free to withdraw my consent without giving a reason. ☐ 2

☐ 3

3. I agree that this form that bears my name and signature may be seen by a designated auditor (i.e. a Chair of the Psychology Ethics Committee or representative of the University Ethics Committee) to monitor correctness of procedure

4. I agree that my non-identifiable research data may be stored in National Archives and used anonymously by others for future research. I am assured that the confidentiality of my data will be upheld through the removal of any personal identifiers. ☐ 4

5. I understand that the data I provide may be used for analysis and subsequent publication, and provide my consent that this might occur. ☐ 5

6. I agree to take part in the above study. ☐ 6

Name of participant	Date	Signature
Name of person taking consent (if different from researcher)	Date	Signature
Researcher	Date	Signature

Debrief sheet:

How do neural responses to touch in peri-personal space (PPS) change during a social compared to a non-social task: measured using EEG and presented in a virtual reality environment?

Thank you for taking part in my study. Peri-personal space (PPS) is defined as the immediate space around the body. Previous research has shown that stimuli within the PPS are attended to faster than when presented in the extra-personal space. Changes have been seen in neural responses when there is tactile stimulation whilst attending to visual stimuli in the PPS, especially when it requires social cognition. However, not much research has investigated this using virtual reality, (which provides a more realistic approach to research), EEG, and tactile stimulation together. Therefore, this study aimed to bridge this gap to investigate whether the task – social or non-social - impacts neural responses (using EEG), as well as using tactile stimulation to explore if there is a difference in responses within the PPS compared to the extra-personal space. The data collected from you will be held anonymously and will not be attributed to you. Once you leave the lab, you will no longer be able to withdraw as your data will be identifiable by the researcher. Feel free to contact the researcher or supervisors if you have any questions through the contact details below.

Regards,

Vanessa Sofia Amaral Lopes Simoes

Version number:
Date:
Contact details:

Researcher:
Name: Vanessa Sofia Amaral Lopes Simoes
Email: VA399@live.mdx.ac.uk

Supervisors:

Name: Dr Jonathan Silas
Email: j.e.silas@mdx.ac.uk
Name: Dr Alexander Jones
Email: a.j.jones@mdx.ac.uk),
Name: Dr Peter Passmore
Email: p.passmore@mdx.ac.uk

TEQ (TEQ; Spreng et al., 2009)

Toronto Empathy Questionnaire instructions

Below is a list of statements. Please read each statement *carefully* and rate how frequently you feel or act in the manner described. Circle your answer on the response form. There are no right or wrong answers or trick questions. Please answer each question as honestly as you can.

	Never	**Rarely**	**Sometimes**	**Often**	**Always**
When someone else is feeling excited, I tend to get excited too	0	1	2	3	4
Other people's misfortunes do not disturb me a great deal	0	1	2	3	4
It upsets me to see someone being treated disrespectfully	0	1	2	3	4
I remain unaffected when someone close to me is happy	0	1	2	3	4
I enjoy making other people feel better	0	1	2	3	4
I have tender, concerned feelings for people less fortunate than me	0	1	2	3	4
When a friend starts to talk about his\her problems, I try to steer the conversation towards something else	0	1	2	3	4
I can tell when others are sad even when they do not say anything	0	1	2	3	4
I find that I am "in tune" with other people's moods	0	1	2	3	4
I do not feel sympathy for people who cause their own serious illnesses	0	1	2	3	4
I become irritated when someone cries	0	1	2	3	4
I am not really interested in how other people feel	0	1	2	3	4
I get a strong urge to help when I see someone who is upset	0	1	2	3	4

When I see someone being treated unfairly, I do not feel very much pity for them	0	1	2	3	4
I find it silly for people to cry out of happiness	0	1	2	3	4
When I see someone being taken advantage of, I feel kind of protective towards him \her	0	1	2	3	4

Table summarising the percentage of correct responses and the number of participants that got each score for the perceptual task:

Percentage of Correct Responses (%)	**Number of participants**
81.25	2
75	7
68.75	3
62.5	8
56.25	6
50	3
43.75	3
37.5	3

The sheet used to take participants' responses:

Videos	What emotions do you think the actors were feeling?	What do you think the actors were talking about?
A1		
A2		
A3		
A4		
A5		
A6		
A7		
A8		

Videos	**Left**	**Right**
A1		
A2		
A3		
A4		
A5		
A6-		
A7		
A8		

Participant advert sheet:

Jones, Silas & Ward Lab

VIRTUAL REALITY & EEG

PARTICIPANTS NEEDED

MUST:
- BE 18+
- NOT HAVE EPILEPSY
- NOT SUFFER FROM MOTION SICKNESS
- NOT BE PREGNANT

£15 AMAZON VOUCHER FOR PARTICIPATION!

SCAN ME!

Hatchcroft Building HG10

CONTACT

Researcher:
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