

The Effects of tDCS on the Processing of Peri-  
Personal Space While Adapting to Different Virtual  
Environments.

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## **Abstract**

In a series of 6 experiments this thesis aimed to explore how the processing of peri-personal space might be affected by changes in sensory information. Previous research has shown that when stimuli is presented within peri-personal space it is processed differently, specifically it has been suggested that there is a prioritisation of space to the area around the hands. If there is a change in processing for the space around us, how might this be affected when interacting with a virtual or augmented environment in which sensory information may be altered? To investigate these changes the MIRAGE mediated reality system was used in which a live video recording of the hand is displayed in real-time in its spatially veridical location, and allows the manipulation of this image and sensory modalities separately. This allowed a more detailed evaluation of previous theories by testing spatial, temporal, and fidelity changes to the hand. Results showed spatial changes between seen and felt hand positions to significantly alter the processing of stimuli presented near and far from the hands. Specifically it was illustrated that a gradual separation between the visual and real hand locations seemed to first create an expansion in the visual receptive fields of bimodal visual-tactile neurons, and second, suggested a remapping of the limbs location to somewhere between the separate representations. Furthermore the application of transcranial direct current stimulation (tDCS), specifically cathodal stimulation, appears to have disrupted proprioceptive feedback, however these effects require further investigation and replication. Results also showed how temporal lag can impair performance on a movement task, while changes in hand fidelity did not significantly alter the processing of peri-personal space. In summary, the experiments presented in this thesis illustrate that spatial changes between seen and felt hand positions significantly alter the way we process space around the hands, and suggest that previous theories need to be re-evaluated and possibly combined to better represent how these changes occur. The findings also have implications for which factors may be most important when exploring

how we process peri-personal space in an augmented or virtual environment.

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# Table of Contents

<b>Chapter 1 Literature Review</b> .....	<b>1</b>
Thesis Overview .....	1
Peri-personal Space and Body Representation .....	2
What is Peri-personal Space? .....	2
Peri-personal Space and Body Representation .....	3
Plasticity and Tool-use .....	3
Body Illusions and Embodiment .....	6
Body Representation and the PPC .....	9
Summary .....	10
Transcranial Direct Current Stimulation (tDCS) .....	10
What is tDCS? .....	10
Modulation of Behaviour .....	11
tDCS and Peri-personal Space .....	12
Summary .....	13
Virtual and Augmented Environments .....	14
Use of Virtual and Augmented Environments .....	14
How Useful is Training in a Virtual Setting? .....	15
Issues in Virtual Reality .....	16
Summary .....	18
The Near Hand Effect .....	18
How Can We Measure Peri-personal Space? .....	18
The Bimodal Neuron Hypothesis .....	26
The Magnocellular Account .....	32
Summary .....	35
Conclusions and Research Aims .....	37

<b>Chapter 2 Pilot</b> .....	<b>38</b>
Methods .....	42
Design .....	42
Participants .....	42
MIRAGE .....	43
Stimuli .....	44
Procedure .....	46
Results .....	49
Outlier Removal .....	49
Reaction Time Analysis .....	50
Discussion .....	53
<b>Chapter 3 The Effect of Spatially Separating the Seen and Felt Hand Locations on Peri-personal Space.</b> .....	<b>58</b>
Methods .....	64
Design .....	64
Participants .....	64
Stimuli .....	64
Procedure .....	66
Results .....	69
Reaction Time Data .....	69
Questionnaire Data .....	72
Discussion .....	74
<b>Chapter 4 The Effects of tDCS on adapting to a Spatial Separation Between Seen and Felt Hand Locations.</b> .....	<b>81</b>
Methods .....	85
Design .....	85
Participants .....	86

Stimuli.....	86
tDCS .....	87
Procedure .....	91
Results .....	94
Reaction time Data .....	94
Questionnaire Data.....	111
Hand Estimation Data .....	114
Discussion.....	115
<b>Chapter 5 The Effects of Appearance Changes to the Hand on the Processing of Peri-hand Space.....</b>	<b>125</b>
Methods.....	132
Design .....	132
Participants.....	132
Stimuli and Equipment .....	132
Procedure .....	134
Results .....	136
Reaction Time Data.....	136
Questionnaire Data.....	137
Discussion.....	139
<b>Chapter 6 The Effects of Temporal Lag on Motor Control and the Processing of Peri-personal Space.....</b>	<b>145</b>
Methods.....	151
Design.....	151
Participants.....	151
Polhemus Liberty Motion Tracker.....	151
Stimuli.....	152
Questionnaire .....	153

Procedure .....	153
Results .....	156
Kinematic Data Analysis .....	156
Reaction Time Data .....	160
Questionnaire Data .....	162
Discussion.....	166
<b>Chapter 7 The Effects of tDCS on adapting to Temporal Lag in a Virtual Environment.....</b>	<b>172</b>
Methods.....	176
Design .....	176
Participants.....	176
Stimuli and Equipment .....	176
tDCS parameters.....	176
Procedure .....	177
Results .....	179
Movement time .....	179
Peak Velocity.....	180
Time to Peak Velocity .....	181
Percentage of Time in the Deceleration Phase.....	182
Angle Error.....	183
Distance Error .....	184
Total Error.....	185
Discussion.....	187
<b>Chapter 8 General Discussion.....</b>	<b>193</b>
<b>Chapter 9 References .....</b>	<b>207</b>
<b>Appendices .....</b>	<b>226</b>
Appendix 1: Edinburgh Handedness Questionnaire .....	226



Appendix 2: Hand Questionnaire (Chapter 3 & 6).....	227
Appendix 3: tDCS Screening Questionnaire .....	228
Appendix 4: Hand Questionnaire (Chapter 4).....	229
Appendix 5: Adverse Effects Questionnaire .....	230
Appendix 6: Questionnaire (Chapter 5) .....	231

# Chapter 1 Literature Review

## Thesis Overview

This thesis investigated the processing of peri-personal space by manipulating spatial, temporal, and visual characteristics of the hand within a virtual environment. It also investigated the effect of a neuromodulation technique, transcranial direct current stimulation (tDCS), to explore any benefits it may offer in overcoming observed changes in how peri-personal space is processed. As the primary measure of how we process the space around the hands reaction time tasks were used that demonstrated the naturally occurring Near Hand Effect (NHE), believed to show changed visual processing for items appearing within peri-personal space. This phenomenon was used to test whether any spatial, temporal, or fidelity changes altered the processing of visual stimuli presented near the hand. These experiments also investigated potential changes in body representation that may directly affect the NHE. Chapter 1 discusses the background literature that led to the experiments presented in this thesis.

Chapter 2 presents a pilot experiment designed to establish firstly whether a NHE is still present within an augmented reality paradigm. Second to reconfirm that it is an effect that is reliant on the hand and not an arbitrary visual anchor. Third, to examine the visual and proprioceptive contributions independently.

Chapters 3 and 4 investigated the impact of a spatial separation between the visual and real hands, which have never before been tested concurrently. This allowed the investigation into what happens to peri-personal space when presented with false visual information. Furthermore chapter 4 employed the use of tDCS to examine its effects at modifying the Posterior Parietal Cortex by potentially altering the way visual and proprioceptive information was being combined.

Chapter 5 examines the effect of changes in fidelity to the visual hand whilst it remained spatially and temporally congruent with the

participant's real limb. This was tested using decreasing levels of realism, first by removing textural detail, second by removing digit definition, and third by removing the little finger, compromising the body representation.

Chapters 6 and 7 investigate the effects of temporal lag on movement alongside an NHE reaction time task. tDCS was then applied to explore whether changes to the PPC and the integration of sensory information could influence movement kinematics including accuracy, movement time, and distance errors. The following literature review details the background research that led to this research thesis. In summary peri-personal space may be altered by fraudulent visual information presented in a virtual or augmented environment, this thesis aimed to explore how peri-personal space changes and whether tDCS could modulate this.

## **Peri-personal Space and Body Representation**

### **What is Peri-personal Space?**

Peri-personal space is described as being the space surrounding the body that lies between the tactile information from the surface and the available visual information outside the body (Claudio. Brozzoli, Makin, Cardinali, Holmes, & Farne, 2012). Often this is referred to as 'graspable space' and is associated with a practical importance of being able to detect things in close proximity, relying on more than just vision.

The notion of peri-personal space has been studied from various viewpoints, including its relationship with body representation, from multisensory processing in monkeys (Graziano, Cooke, & Taylor, 2000; Graziano, 1999) through to the body schema and the incorporation of additional limbs (Newport, Pearce, & Preston, 2010; Newport & Preston, 2011; Preston & Newport, 2011). The high degree of multisensory integration between vision, audition, and touch, which does not occur to the same extent for extra-personal space, is a key characteristic of peri-personal space. The following sections discuss peri-personal space in relation to body representation, evidence of its plasticity, the influence of body illusions, and the possible changes in VR.

### **Peri-personal Space and Body Representation**

The body is thought to be represented in at least two distinct ways, body schema and body image. Although there is debate within the literature as to the exact definitions of these concepts, it is broadly agreed that schema relates to sensorimotor representations to aid in movement, while body image relates to perceptual information about the body (De Vignemont, 2010; Dijkerman and De Haan, 2007). In order to carry out a successful movement the brain must be aware of the size, location, and orientation of the limb if it is to interact with the environment. It is suggested that the body schema is responsible for representing and updating this information, combining proprioception, touch, and kinesthesia (Cardinali, Brozzoli, & Farnè, 2009). Therefore the body schema is likely necessary for the accurate representation of peri-personal space.

Peri-personal space and body representation have been primarily linked through observations in Macaque monkey's using single cell unit recordings. The research has suggested that continued representation of peri-personal space is reliant partly on bimodal visual tactile neurons. These neurons possess receptive fields that move based on the position of the body, rather than being retinal centric (Graziano & Gross, 1993; Graziano, 1999; Graziano and Gross, 1995). They have tactile receptive fields on the limb with corresponding visual receptive fields that extend beyond the limb and into the surrounding space. They demonstrate a real-time encoding of the space around the body, regardless of where we are attending to. Since these neurons shift with limb movement they must rely on an up-to-date representation of body location, or act as a means of providing this. Nevertheless it is reasonable to assume that the encoding of body/limb location in space also informs the location and boundaries of peri-personal space.

### **Plasticity and Tool-use**

Human studies have also investigated peri-personal space based on the integration of sensory information, specifically vision, touch, and proprioception (Maravita, Spence, & Driver, 2003). Peri-personal space is thought to extend 20-40cm in monkeys, and up to 70cm in humans

(Holmes & Spence, 2004). Additionally, peri-personal space must adapt over time in order to maintain an accurate representation of our bodies as we grow.

There is evidence to suggest that an extension of peri-personal space can occur through the use of tools. Research by Iriki, Tanaka, and Iwamura (1996) argued that bimodal neurons were responsible for this adaptation, proposing that the body schema may be coded by these neurons. They trained monkeys to reach for food pellets both using their hand or a rake and found that during tool use neurons responded to items further away than in the hand condition demonstrating an expansion of the visual receptive field's (vRF). This research suggested that peri-personal space may expand to the tip of the tool and that the vRF itself may be altered in shape and size to encompass a functional tool. Arguably this demonstrates an expansion, but also a 'remapping' of the space since the vRF's adapted to the shape of the tool and were focused around it rather than merely expanding into more space.

It has also been argued that the tool may be incorporated into the Body Image (Obayashi et al., 2001). This was demonstrated in monkeys through the use of positron emission tomography (PET) showing significant increases in blood flow during tool use compared to the control condition, of particular note in the intraparietal sulcus, an area known to contain bimodal visual tactile neurons. However, these findings have been called in to question due to the fact that no sizes or measurements for any changes in peri-personal space were provided. Furthermore it has been suggested that these changes could have been the result of chance (Holmes, 2012).

Neurological evidence in humans has also shown possible re-mapping of peri-personal space through the use of tools. This is often demonstrated by increased severity of cross modal extinction elicited by visual stimuli presented at the end of a reaching tool (Bonifazi, Farnè, Rinaldesi, & Làdavas, 2007). By demonstrating changes in extinction these studies support monkey literature that suggests peri-personal space is based on

multimodal neurons (Maravita, Husain, Clarke, & Driver, 2001). Farne and Ladavas (2000) found evidence to suggest that tool use temporarily expanded peri-personal space by showing that patients with tactile extinction displayed more severe cross modal extinction after using a rake compared to the no tool condition. They argued that making a motor action in the direction of the target without a tool (and therefore unreachable) did not modify peri-personal space, however when a tool was used the far placed item becomes accessible and promotes the extension of peri-personal space temporarily. This extension was observed for several minutes after the tool was removed highlighting the adaptive nature of peri-personal space. Other research has suggested that a tool can be incorporated in to the body schema for up to 15 minutes (Cardinali et al., 2009). Importantly it has been shown that it is using the tool that creates these changes, rather than passively holding the tool (Farnè, Bonifazi, & Ladavas, 2005). Conversely in blind individuals who regularly used a cane, just holding a rod passively immediately expanded their peri-personal space suggesting that through repetitive use of tools this extension can become durable (Serino, Bassolino, Farnè, & Ladavas, 2007).

However, despite this evidence of modulation of peri-personal space following tool use, further evaluation is required. For example, many early studies investigating tool use only examined responses at the tips of the tool. Therefore it is not clear whether it is an expansion of peri-personal space, encompassing the entire rake, or whether two distinct zones have been created (Holmes, 2012). To evaluate this effect in humans, Holmes, Calvert, and Spence (2004) proposed four alternative hypotheses. In summary, either tool use expanded the vRF around the entire tool including the hand: the vRF moved to the end of the tool: vRF remained around the hand while another was created at the tools tip: or the vRF remained around the hand only. They used a crossmodal congruency task in which participants had to identify which finger they felt vibrotactile stimulation on whilst ignoring distractor visual stimuli appearing at different locations on the tool. Their results suggested that

rather than a simple extension of peri-personal space, tool use created an additional zone at the tip of the tool, but not the middle.

Another study sought to investigate this by measuring responses at different points along the tool. They concluded that there seems to be an elongation of space stretching from the hand up the length of the tool to the tip (Bonifazi et al., 2007). This contradicts what Holmes et al. (2004) found but the authors suggested the contrast in results could be due to the stimuli used i.e. Holmes et al used a handled stick to press buttons while their study used a rake. It could be argued that a stick is not as functional as a rake, nor are their functions exactly alike which could imply that the function of the tool is a factor in how peri-personal space is altered.

It is evident from these examples that peri-personal space is changeable and likely relies on the expansion of vRFs of bimodal neurons to process new regions of space in a body centred, multimodal way. The next section discusses examples of how our body representation can be manipulated through the use of illusions that distort sensory information.

### **Body Illusions and Embodiment**

Alternative evidence to support the notion of changes in peri-personal space in humans comes from visual-tactile illusions that may alter the representation of the body. Rubber Hand Illusion (RHI) research, in which a person takes ownership over a fake rubber hand through synchronous visual and tactile input (Botvinick & Cohen, 1998), or a virtual hand (Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008), has suggested that the space surrounding the fake hand may become represented as peri-personal space (Làdavas & Farnè, 2004). It is this new representation that allows the sensation of touch to be perceived on the rubber hand in addition to the real hand.

Similarly, fMRI research in which a fake hand is viewed has shown similar patterns of activation in the PPC as when a real hand is observed (Makin, Holmes, & Zohary, 2007; Perani et al., 2001) therefore suggesting that a convincing fake limb might be encoded in to the body image and/or schema. Research using the MIRAGE (see methods in

chapter 2) has specifically investigated how fake limbs may or may not be accepted in to the body image/schema and the influence of incongruent sensory information regarding the limb. In one study it was shown that the believed location of the limb can be manipulated and participants will accept a fake limb to belong to them if it appeared to touch the target i.e. when they appeared to accurately reach their target they accepted ownership over the limb despite it being spatially incongruent to their real limb location (Preston & Newport, 2010), demonstrating that creating successful movements can create feelings of ownership that overcome spatial incongruence with the real limb location. In another study it was shown that two hands can have perceived ownership when tactile and visual information (stroking of the hand) was synchronous. This ownership disappeared when the sensory input became incongruent for one of the hands (regardless of the real hand location, the synchronous tactile one was accepted). Furthermore when both hands were accepted into the body image, only one could be incorporated into the body schema which was always the congruently stroked one as measured by a reaching movement (Newport et al., 2010). These examples highlight how illusory information can influence body image as well as schema and suggests that peri-personal space as a result may be readily manipulated.

In addition, another study using the MIRAGE investigated how to disrupt or prevent embodiment, rather than factors creating it (Preston & Newport, 2011). This was based on patient studies in which they reject their own limb, usually as the result of right hemisphere brain damage (Vallar & Ronchi, 2009), but also physical limitations such as knowing that a physical object can't pass through your body (Saxe, Tzelnic, & Carey, 2006). They recorded ownership questionnaire responses for different conditions which involved them viewing a stick pass through a visual representation of their hand within MIRAGE. It was expected that by violating physical laws ownership for the encroached hand would be lost/reduced. Visual hands were either close to the midline or further away. The results showed that when a hand was encroached by the stick ownership ratings dropped. However, interestingly this only happened for



the hand furthest from the body. Despite violating knowledge that a stick can not pass through the hand, the hand closest to the midline maintained high ownership scores. The authors suggest that proximity to the midline could be a vital factor in determining the most likely real limb as you are unlikely to ever see an arm belong to someone else that close to your midline from a first person perspective. Furthermore, it has been suggested that proprioception is more heavily weighted than vision when the real limb is closer to the midline (Van Beers, Sittig, & Denier Van Der Gon, 1998). Therefore in the study by Preston and Newport in which the real hand was further from the midline than the fake visual hand, perhaps the proprioceptive information was still being dominated by vision.

Similarly, the use of rubber hands to investigate the effect of changes in orientation of the limb have shown that when the limb is placed in an implausible position it has little or no effect on a crossmodal congruency task (Pavani, Spence, & Driver, 2000). Furthermore, visual processing has been shown to change depending on the intent of the observer in terms of action. In other words, if an item is intended to be grasped (presumably within graspable space) accuracy in identifying the item with the correct orientation, amongst distractors, increases (Bekkering & Neggers, 2002). The authors showed that orientation, not colour, influenced accuracy when grasping a target object as measured by fewer saccades when reaching to an object instead of just pointing. They argued that this was evidence of a change in visual processing as a result of the intention to interact with the object, specifically stating that action-relevant features are represented with a higher resolution in order to aid the planning of action. This could also suggest that items within peri-personal space receive additional processing, in terms of shape and orientation, to assess how best to interact with it (relating to the m-cell account above). This process may be further facilitated by hand proximity as the hand would likely be the effector used to interact with the item. Together these results suggest that body representation can be deceived by fraudulent visual information, however there are limits to this in terms of believability.

Spatial limits between the real and fake hand have been observed showing that a separation of over 30cm can lead to the RHI being less effective, this suggests that peri-hand space is being extended (to the rubber hand) but that it has spatial limits (Lloyd, 2007). This 30cm limit has also been suggested as the boundary for peri-personal space (Bonifazi et al., 2007).

### **Body Representation and the PPC**

The PPC is known to be involved both the encoding of peri-personal space (Avenanti, Annala, & Serino, 2012; Serino et al., 2011) and of sensory information relating to the body (Bolognini & Maravita, 2007; Hagura et al., 2007) and specifically the hand (Dufour & Touzalin, 2008; Sakata, Takaoka, Kawarasaki, & Shibutani, 1973). Additionally, premotor regions have been linked to the encoding of peri-personal space in hand-centred co-ordinates, along with the PPC (Claudio Brozzoli, Gentile, & Ehrsson, 2012). For example, sounds presented within peri-personal space reduced reaction times to tactile targets but not in extra-personal space (Serino, Canzoneri, & Avenanti, 2011). When Transcranial Magnetic Stimulation (TMS) was applied to the premotor cortex (PMC) and the Posterior Parietal Cortex (PPC) this facilitation effect was abolished indicating vital roles for both the PMC and PPC in the representation of multisensory information relating to peri-personal space. Additionally both premotor and parietal areas encode body parts in a visually dominant way due to their preference for higher spatial acuity (Giummarra, Gibson, Georgiou-Karistianis, & Bradshaw, 2008).

Neurostimulation studies have also demonstrated how disruptions to the PPC can critically influence the processing of stimuli appearing in peri-personal space. For example, TMS applied to the PPC has been shown to reduce multisensory integration relating to the visual-tactile information regarding the hand (Pasalar, Ro, & Beauchamp, 2010), and disrupt path correction to targets in near hand space (Desmurget et al., 1999), while TMS to the temporal parietal junction has been shown to disrupt the integration of an illusory limb (Tsakiris, Carpenter, James, & Fotopoulou, 2010). Additionally, transcranial direct current stimulation (tDCS) has

been shown to enhance spatial orienting to targets within peri-personal space (Bolognini, Olgiati, Rossetti, & Maravita, 2010).

Neurological evidence from patients with right hemisphere brain damage has also highlighted that peri-personal space is represented differently to other types of space. Due to items in close proximity being candidates for action it makes sense for the brain to process items in peri-personal space differently to those in extra-personal space (non-graspable space). This difference between tasks performed in different spaces has been demonstrated in patient studies following right hemisphere damage. Patients were unable to perform a line bisection task using a pen and paper (within peri-personal space) but were able to accomplish the task when given a laser pointer allowing them to bisect a line now further away (Halligan & Marshall, 1991). Additionally, the right PPC has been shown to be involved in search for near space, but not for far suggesting a dissociation between dorsal and ventral streams (Lane, Ball, Smith, Schenk, & Ellison, 2013). This indicates that neurologically peri-personal space is different to extra-personal space.

### **Summary**

Peri-personal space is processed differently to other kinds of space, possibly serving an evolutionary purpose such as threat detection or effective tool use. The way this space is represented can likely be influenced by body illusions as a result of changes in the body schema or image. Tool-use studies have highlighted the adaptive nature of peri-personal space however it is currently unclear how a virtual effector may change this representation.

## **Transcranial Direct Current Stimulation (tDCS)**

### **What is tDCS?**

Transcranial direct current stimulation (tDCS) is a method of non-invasive brain stimulation that has been shown to modulate performance on various tasks as a result of targeting brain regions associated with task requirements (Nitsche & Paulus, 2000; Nitsche & Paulus, 2001). From cognitive studies demonstrating changes in learning (Iuculano & Cohen

Kadosh, 2013), improved working memory (Martin et al., 2013) and changes in mathematical skills (Thomas, 2010), to motor studies examining increased skill acquisition (Reis et al., 2009) and motor function improvement in stroke patients (Boggio et al., 2007).

Like TMS, tDCS can modulate performance on a task, however while TMS is usually disruptive to the targeted cortical area, tDCS has two polarities which should modulate the cortex in a more subtle way by increasing or decreasing the likelihood of action potentials. Anodal stimulation (+ve current) depolarises the neurons, increasing the probability of action potentials, whilst cathodal stimulation (-ve current) hyperpolarises neurons, decreasing the likelihood of action potentials (Nitsche et al., 2008). The current is applied through the use of two small electrodes that are placed on the scalp (See Chapter 4 for figures and further description). The target electrode is placed over the region of interest, while the reference electrode is usually placed on the contralateral side of the head so that the current is drawn through the brain from one electrode to the other, rather than through the cerebral spinal fluid (CSF) which may happen if they are placed too close together. The polarity of stimulation simply refers to the direction of the current, i.e. in the anodal session the current is flowing from the target electrode towards the reference. It is the directional flow of the current that influences the polarisation of the neurons (Nitsche & Paulus, 2001).

### **Modulation of Behaviour**

Generally it has been shown that anodal stimulation, through temporary modulation of the cortex, facilitates behaviours, while cathodal stimulation has the polar effect of inhibiting behaviours (Antal, Kincses, Nitsche, & Paulus, 2003; Nitsche et al., 2008; Priori, 2003; Shimizu, Wu, Samra, & Knowlton, 2017). Comparisons between these two polarities have been observed in several contexts including motor processing (Nitsche & Paulus, 2000; Pellicciari, Brignani, & Miniussi, 2013), language (Ehrlis, Haussinger, Gastel, Fallgatter, & Plewnia, 2016; Meinzer et al., 2014), and visual processing (Antal et al., 2003; Antal, Nitsche, & Paulus, 2001). Furthermore it has been suggested that

stimulation to one region can influence the entire network (Catani, Jones, & ffytche, 2005; Jacobson, Koslowsky, & Lavidor, 2012) therefore although both the PPC and PMC have been implicated in the processing of sensory information pertaining to body representation and peri-personal space, stimulating just one of these regions could have implications for the whole network.

However, the influence of stimulation intensity has been shown to alter the polarity specific effect with intensities over 2mA showing only excitatory changes (Batsikadze, Moliadze, Paulus, Kuo, & Nitsche, 2013). Furthermore, for presently unknown reasons several studies have reported disruptive effects on task performance as a results of either type of stimulation polarity (Filmer, Dux, & Mattingley, 2015; Filmer, Mattingley, Marois, & Dux, 2013). This suggests that although polarity specific effects have been established, tDCS is not always reliable in producing them, and depending on area of stimulation and task demands both polarities can have the same effect.

Despite the uncertain nature of tDCS, many studies have shown significant changes in behaviour as a result of its application. Therefore both anodal and cathodal protocols were used for research presented in this thesis to examine its potential as a tool for modulation sensory integration in peri-personal space. In chapter 4 it was used to try to overcome the changes to the NHE as a result of the spatial separation between visual and proprioceptive information, while in chapter 7 it was used to investigate adapting to a temporal lag when making reaching movements.

### **tDCS and Peri-personal Space**

Previous research using brain stimulation to investigate changes in the processing of peri-personal space and body representation have primarily used TMS (Pasalar et al., 2010; Tsakiris et al., 2010), however this is usually disruptive rather than enhancing. Stimulation to the PPC has been shown to disrupt several tasks which require interaction with peri-personal space including visual search (Ashbridge, Walsh, & Cowey,

1997), line bisection tasks (Ellison, Schindler, Pattison, & Milner, 2013), and reaching movements to targets (Johnson & Haggard, 2005). Therefore tDCS (to the PPC) was chosen to be the subject of investigation for potential tool use as one or both polarities could improve performance on a task. The main purpose of exploring the use of tDCS was to establish whether it could improve or overcome any issues that might be found when testing the NHE in different VR conditions. Due to significant changes only being found for the spatial and temporal changes, tDCS was used to further investigate these issues, whereas appearance changes did not significantly alter performance and therefore there was no need to find a way to improve performance with tDCS.

If a benefit of tDCS was observed then this could potentially be used alongside VR training to improve its efficiency and transferability of skills learnt to a real world setting. Particularly in relation to motor skill training such as medical field simulations, identifying a way to overcome VR lag issues could mean the development of higher fidelity systems while avoiding the cost of lag on performance. Several studies have investigated the effects of tDCS as a tool to assist training and shown improvements with anodal stimulation (Nitsche et al., 2003), yet also disruptions to motor training (Stagg et al., 2011). It has been argued that neuro-stimulation can effect training due to changes in plasticity and support the idea that tDCS could be used to alter the effect of training.

Furthermore, evidence has shown that when there is a large incongruence between vision and somatosensory input a visuo-tactile enhancement is created, but this can be disrupted through the use of TMS to the PPC, thus highlighting its role in compensating for sensory mismatch (Ro, Wallace, Hadedorn, Farne, & Pienkos, 2004).

### **Summary**

tDCS has been shown to modulate behaviour on a variety of tasks that relate to the processing of peri-personal space, and could therefore be used to investigate changes in the experiments presented in this thesis through

modulation of the PPC. A more detailed evaluation of PPC modulation can be found in chapters 4 and 7.

With evidence suggesting peri-personal space and the body schema can be manipulated, either through vision of a fake limb or congruent illusory sensory information, it is possible that this results in changes to how we process the space around us. The use of virtual and augmented reality systems are a prime example of the use of illusory and incongruent multisensory information and is discussed in detail in the following section.

## **Virtual and Augmented Environments**

### **Use of Virtual and Augmented Environments**

The adaptive nature of peri-personal space through tool use or bodily illusions suggests questions for the use of VR limbs, or limbs positioned within an augmented or virtual environment. How might a virtual limb create a representation of peri-personal space? It's also been shown that VR limbs, or limbs in a virtual environment, can be embodied in to the body schema which likely changes the representation of peri-personal space (Slater et al., 2008; Perez-Marcos, Slater, & Sanchez-Vives, 2009). What is currently unclear is what might happen to the processing of items near a virtual hand in which sensory information is being processed in different ways. Virtual reality and augmented reality (AR; where virtual objects are displayed within a real environment) are fast growing, developing areas and have seen huge expansion in the gaming sector, as rehabilitation tools, and their use as tools for training (Adamovich, Fluet, Tunik, & Merians, 2009; Reger et al., 2016; Schmitt, Agarwal, & Prestigiacomio, 2012). Augmented reality is becoming more popular recently, for example Microsoft HoloLens, in which the virtual objects are viewed within the user's real environment and appear to be part of the real world (Nabiyouni, Scerbo, Bowman, & Höllerer, 2017), while virtual reality is more traditionally used for things such as flight simulators.

In particular, the military are considering increasing its use of VR as an alternative to field training whilst weighing up if it is cost effective

(Wilson, 2008). Training personnel in a virtual or augmented environment has the advantage of observing an individual in a hazardous setting without actually putting them in danger. This allows people to practise tasks in high risk scenarios which may otherwise be unavailable (Satava, 2008). Furthermore with the addition of other technologies many metrics relating to performance can be quantified. For example, eye-tracking combined with hand tracking has been used to explore the user's abilities and reactions to difficult procedures (Satava, 2008). Flight simulators also provide a variety of metrics that could show points at which deviations are made, or other performance related data.

### **How Useful is Training in a Virtual Setting?**

Studies have reported that after training in a surgical simulator surgeons made fewer errors, performed procedures quicker, and showed improvements in accuracy (Aggarwal et al., 2007; Reznick & MacRae, 2006). Furthermore, Kamarainen et al., (2013) stated that instructions were more effective, trainees were more motivated, and better engaged when accompanied by AR training. The U.S. military have employed the use of the Augmented Immersive Team Trainer (AITT) which has its benefit in being a portable system with outdoor capabilities. Research has investigated how useful this system is for training purposes and showed that users were unable to make use of all their other tools (that they would use in a real life scenario) with this likely being due to the head mounted display being worn. Removing this to use other tools created small issues that were reported by the users, lowering their satisfaction (Champney, Lackey, Stanney, & Quinn, 2015). In addition, the usability of the system did not receive particularly high ratings with users reporting that the technical setup was intimidating. However they did report lower levels of simulator sickness than VR systems. Other AR systems such as the Anti-Air Warfare Coordinator have shown more promising results in trainees showing higher situation awareness compared to controls (Kim, Chan, & Du, 2015).



### **Issues in Virtual Reality**

A core reason VR and AR systems might not always meet user's needs is that sensory input is not created in the same way as the real world, for example all VR/AR systems require processing time in which it takes feedback from the user and updates the visual output based on this. This inevitably creates a lag, or delay, on the system. In more recent systems this is undetectable due to humans being unable to detect lag less than 20ms (Hirsh & Sherrick Jr, 1961). However, the demand for VR/AR systems to be more realistic can come at the cost of system processing time, meaning developers now need to balance the desire for fidelity with speed (Kaber, Li, Clamann, & Lee, 2012). Furthermore the distance between the operator and the resulting output can influence transmission delays and may mean that lag on even a modern high specification system is still being created (Ottensmeyer, Hu, Thompson, Ren, & Sheridan, 2000). Therefore it is vital that we understand how much of a problem, if any, temporal lag is to performance in VR and any effect on the processing of peri-personal space, and secondly is there a way to alter these changes to improve performance, overcoming the issue through the use of tDCS.

Latency in VR and AR systems has been suggested to be the most problematic issue (Nabiyouni et al., 2017), with multiple sources of lag such as rendering, tracking and end-to-end latency. The effect of lag on performance in VR has previously been difficult to investigate, but detriments in levels of immersion, comfort, and performance have been observed (Friston & Steed, 2014; Jay & Hubbard, 2005; MacKenzie & Ware, 1993). Chapter 6 explores the effect of temporal lag on the processing of peri-personal space and movements in a virtual setting.

The above mentioned processing or design issues in VR mean that often what we are seeing (i.e. a virtual hand) and what we are feeling (where we feel movement i.e. proprioception) will create incongruent sensory information. Since body representation and that of peri-personal space rely on the convergence of sensory information it stands to reason that using a VR/AR system will change this representation by altering multisensory integration.

Some research has shown that a virtual arm can be embodied through synchronous tactile and visual feedback (Slater et al., 2008) however it has also been argued that when in a virtual environment users have to make use of other processes to interact with their environment due to being spatially disembodied (Arnold & Farrell, 2003). Furthermore, when visual and proprioceptive sensory inputs arise from different sources, they may not be integrated the same way, often with vision being treated as dominant (Congedo, Lécuyer, & Gentaz, 2006). This has implications for the representation of peri-personal space for both the fake visual, and real hands. Therefore it's important to understand the impact of a spatial separation between the controller and the effector. Chapters 2 and 3 investigate the consequences of a spatial separation between the controlled limb and the visual output. Additionally chapter 4 explores the use of tDCS on altering how space is processed around the hand when visual and proprioceptive inputs are not congruent.

An additional factor to consider for VR/AR training is the appearance of the effector. Often users are controlling an avatar or tool that does not resemble their real hand. Therefore it is important to understand what effect appearance has on peri-personal space when controlling a fake limb. Fidelity in VR training could be less important than other factors, with research showing that junior surgeons benefited equally from the high and low fidelity simulators perhaps indicating a relationship between level of expertise and the benefit of training in a simulator (Anastakis et al., 1999; Matsumoto, Hamstra, Radomski, & Cusimano, 2002). Those with more experience may see a greater benefit from the high fidelity systems as they've already learn the basic spatial procedure. Furthermore research investigating the use of army helicopter simulators also found the same rates of effective transfer of learning for both high and low fidelity simulators (Stewart, Johnson, & Howse, 2008). Conversely, VR fidelity has been shown to have a causal relationship with anxiety in sports training suggesting more subtle effects of fidelity that might not affect peri-personal space or kinematics (Stinson & Bowman, 2014). To explore the

effect of fidelity further, chapter 5 investigated how changes in fidelity of a virtual hand effected the processing of peri-personal space.

### **Summary**

There is a wide variety of applications for VR/AR systems by the military which include medical training, aviation simulators, combat scenarios, and as a stress management tool (Pallavicini, Argenton, Toniuzzi, Aceti, & Mantovani, 2016; Reger et al., 2016). If continued investment is planned it is vital that we understand how the above issues with these systems (temporal lag, spatial separation, and fidelity) might be influencing behaviour. The following section discusses how to measure changes in peri-personal space, through the Near Hand Effect.

## **The Near Hand Effect**

### **How Can We Measure Peri-personal Space?**

A great body of research in the last ten years has established that items near the hand, or within the peri-personal space, are processed differently than items further away (Abrams, Davoli, Du, Knapp Iii, & Paull, 2008; Adam, Bovend'Eerd, van Dooren, Fischer, & Pratt, 2012; Adam & Moresi, 2007; Davoli, Du, Montana, Gaverick, & Abrams, 2010; Tseng & Bridgeman, 2011; Weidler & Abrams, 2013). The following section will summarise research investigating this, and present and evaluate the key theories.

The first time this Near Hand Effect (NHE) was observed in humans was the study by Reed, Grubb and Steele (2006) who showed a facilitation effect for targets appearing near to the hand. In a series of 5 experiments, they highlighted not only that the presence of the hand could affect visual processing, but also the nature of this facilitation. Their reasoning for beginning this investigation was that items that appear near the body, in peri-personal space, are graspable. In other words, we are able to interact with them, and sometimes they with us. Obviously items within such close proximity could pose a threat, as well as being of use. Therefore it stands to reason that we should be better able to detect items in peri-personal space, not only to help identify possible tools, but also in order

to better protect ourselves. Their argument was that placing the hand near an object could potentially change how we attend to it and aimed to investigate two possible mechanisms: the prioritisation of space, and the shifting of attention.

The first experiment in their series involved participants completing a covert orienting paradigm on a computer monitor (Posner, Walker, Friedrich, & Rafal, 1987). In this task participants had to respond to targets that were presented in one of two possible locations. Between these target locations was a cue that predicted the location of the next target in a highly predictive way (70%). Participants' responses were recorded to both the validly cued trials and the invalid cued trials. Whilst performing this task participants placed their hand next to the target location (their right hand on the right target side, their left on the left target side). Each hand was tested one at a time, making their responses with the free hand via a mouse on the table. The hand was positioned thumb side up, with the palm facing towards the centre of the screen. This now classic set up of placing the hand near the stimulus means that it is now appearing in near-hand space compared to having the hands placed passively in their lap; far hand space. What they observed was that this simple act of having the hand placed next to one set of targets facilitated reaction times to targets appearing near the hand, regardless of cue validity.

This result was in line with their predictions which argued that the hand would be recruiting the use of bimodal visual-tactile neurons that help to represent the space around the hand (discussed in detail in the following subsection). This in turn would prioritise the space and consequently lead to a decrease in reaction times. For the hand to create a biasing of attention it was expected that all targets near the hand would see a facilitation, including those which were invalidly cued. Alternatively they argued that if the validly cued targets were responded to relatively faster, then this could indicate a shifting of attention.

Specifically, they observed a basic effect of cue validity in which validly cued targets received faster reaction times. Second, quicker reaction times

when the right (dominant) hand was responding. But most importantly, they observed that hand presence significantly decreased reaction times to targets near the hand. However the four-way interaction including validity was not significant highlighting that this facilitation occurred for both valid and invalidly cued targets. Furthermore no facilitation was observed when the hand was not presented next to the stimuli.

However, these results did not exclude the possibility that the mere presence of an additional visual stimuli could have the same effect on attention, and bias an area of space. Therefore they devised a second experiment using an arbitrary visual anchor to ensure that this would not have the same effect as the presence of the hand in experiment 1. A hand sized board was presented in place of the hand next to the screen in both left side and right side conditions. The board conditions were compared against hand conditions as seen in the first experiment. As expected a main effect of cue validity was found. Importantly only targets appearing near the hand saw a facilitation compared to those appearing away from the hand, meaning that when a hand sized board was positioned next to the targets no facilitation was shown. These results suggest that it is the proximity of the hand itself that changes reaction times to targets, and this can not be recreated using an arbitrary visual anchor.

These first two experiments could not be used to support the role of bimodal visual tactile neurons however, due to the unimodal nature of the task. Therefore a third experiment was conducted to examine the proprioceptive contribution of hand presence. The receptive fields of bimodal neurons are thought to move with the limb suggesting that with the hand presented next to a stimulus the visual receptive fields (vRF), which extend beyond the tactile receptive fields (tRF) on the hand and into the space around it, should detect the stimuli. Since these move with the hand, proprioceptive information regarding hand location should influence the location of these receptive fields, even without vision of the limb. It was reasoned that if bimodal neurons play a role in this near hand facilitation effect then the proprioceptive input from the hand should be

sufficient to generate a facilitation without vision of the hand due to the positioning of the vRFs.

As in the previous experiments participants placed their hand next to the side of the screen but this time it was covered from view with a black box. This condition was then compared to a fully visible hand condition. Results showed a significant interaction for hand side and target side suggesting that near hand targets were responded to faster than far targets for both the normal hand condition and the proprioceptive only condition. However post hoc analysis with separate ANOVA's revealed that it was only significant for the normal hand. The authors suggested that the effect for proprioceptive contributions was therefore less reliable but still present.

Due to evidence that bimodal neurons may also respond to a convincing yet fake limb (Graziano, 1999), for their fourth experiment participants viewed a rubber hand next to the stimuli while their real hand lay on their laps. Furthermore participants were asked to wear a rubber glove on their concealed hand so that the hand they saw felt more like their own. As they expected, reaction times were faster to near targets with no significant difference between the normal hand and the fake hand condition. However, as in experiment 3, further separate testing revealed the effect to be less reliable for the fake hand condition. The evidence presented in these experiments was used to conclude that bimodal visual-tactile neurons play a key role in the observed NHE.

One last experiment was devised to investigate whether the effect was graded by distance between the hand and targets. Targets were presented at various distances from the hand including those outside of graspable space. Results from this experiment differed from the previous ones in that the facilitation was stronger for validly cued trials. However overall results showed faster reaction times to targets appearing closest to the hand and within the same hemi-field. It was concluded that this again supports the role of bimodal neurons in prioritising attention to items close to the hand. If hand presence had shifted attention instead then

validly cued targets on the far side of space would have seen no difference in reaction times to invalid cues, however main effects of cue validity were found across experiments. Importantly they showed that as target distance from the hand increased so did reaction times suggesting proximity to the hand effects the strength of the facilitation.

The outcome of the fourth experiment in which a fake limb elicited a NHE they argued was evidence that vision dominates over proprioceptive information. However this may not necessarily be true as they did not test the relative contribution of the proprioceptive hand at the same time the visual fake limb was being tested. However it can be concluded that visual information that resembles the hand seems to be enough of a contribution to elicit an effect, yet this may not indicate a stronger or dominant effect of vision as the proprioceptive hand experiment produced similar results.

Since this initial discovery that hand proximity can influence attention numerous other studies have used different paradigms to further evaluate the claims. One such study investigated three classic attention tasks and the impact of hand proximity including visual search, attentional blink, and inhibition of return (Abrams, Davoli, Du, Knapp Iii, & Paull, 2008). According to the study by Reed et al., having the hands placed near the task should prioritise space around the hand, however when searching for a particular target how would hand presence affect performance? A visual search task would further evaluate the findings by Reed and offer insight into how hand presence effects the processing of peri-personal space, and stimuli within it.

It was hypothesised that this attentional bias towards the hand may be mediated by bimodal neurons that are processing space in a hand-centred way. Therefore it was suggested that hand proximity may not simply facilitate detection of stimuli appearing close to the hand, but create preferential processing of the stimuli allowing detailed evaluation by altering visual processing. This would clearly be a more useful function than mere detection. The three paradigms were therefore chosen to examine any changes in visual processing of stimuli near the hands.

The visual search task was completed in two conditions, with hands on their laps or hands next to the sides of the monitor. In both conditions response buttons were placed under their hands. Button responses corresponded to target letters that were hidden amongst distractors. Participants received feedback messages on screen between trials if they were too fast, slow, or gave an incorrect response. This set up was tested in several slightly altered sub experiments: the hands were shielded from view when placed next to the screen and secondly hand responses were removed and replaced with a foot pedal response.

Results showed a slower rate of search in conditions where the hands were placed next to the screen in all three sub experiments. The authors concluded that hand proximity prolonged the processing of the stimuli in order to allow a more detailed evaluation of the scene. Notably this extended search time was also present when the hands were shielded from view suggesting vision of the hand is not necessary for this to occur. Abrams et al. referred to this result as the detailed evaluation theory. Furthermore the foot-pedal response condition saw the same pattern of results highlighting that hand proximity was not affecting the motor requirements of responding. A key point to note is that the present study asked participants to place both hands at the sides of the monitor rather than one at a time as in Reed et al. (2006). By not testing both hands together they were able to conclude that one hemifield had been biased, however this evidence would suggest there is more to hand proximity than biasing of attention and does reflect changes in the nature of processing of visual stimuli.

What remained unclear from experiment 1's results was whether prolonged visual search time was evidence of delayed disengagement of attention from one search item to the next, or of delayed engagement to the stimuli. To test this experiment 2 employed a classic inhibition of return task which had either a 300ms delay between cue and target, or 950ms. Results found an inhibitory disadvantage for the 950ms cued target location but not at 300ms suggesting a problem disengaging from the cued object when the hand was presented near the task. The results of



this experiment were concluded to support the findings of the first by suggesting that each item in the visual search received further processing due to hand proximity meaning it took longer to disengage from one to the next, increasing overall search time.

In their final experiment the effect of attention over time was investigated. This was an attentional blink task that required participants to identify two targets presented in a string with the likelihood being that they can not attend to a second target if it appears in immediate succession from the first (Shapiro, Raymond, & Arnell, 1997). This inability to attend to the second target presented within 500ms is referred to as an attentional blink. It has been suggested that this reflects the processing time required before being able to attend to another stimulus (Nieuwenstein, Potter, & Theeuwes, 2009). Therefore it was expected that hands placed near the stimuli could reduce accuracy in identification of the second target due to a delay in the ability to disengage attention from the first target. Results confirmed the hypothesis showing an increased attentional blink when the hands were placed near the display. This effect was consistent across the task and did not change depending on the amount of distractor targets presented between targets 1 and 2. The results from these experiments suggest a more detailed level of processing for items appearing in peri-hand space which would explain a longer disengagement of attention to allow for further evaluation to occur, whether to assess threat or potential tool use.

The influence of hand proximity on cognitive control was investigated by Weidler and Abrams (2013) based on the idea that changes in perceptual processes might also affect cognition. Additionally to be able to focus attention or ignore distractor information cognitive control must be exercised. Using both a flanker and task switching task they showed reduced interference when the hands were proximal to the stimuli. The authors concluded that this was evidence of increased cognitive control near the hands, postulating that more control is needed in order to prevent inappropriate action.

Changes in working memory have also been investigated showing hand proximity to be an influencing factor. Tseng and Bridgeman (2011) carried out a group of experiments beginning with a change detection task which recruits the use of visual short term memory (VSTM). This kind of task is more complex than most commonly used cognitive tasks and requires the participant to constantly encode and retrieve visual information (Luck & Vogel, 1997). Their results showed that participants were able to hold more memories when their hands were placed next to the stimuli. They concluded that this change in performance on a VSTM task was evidence of changes in attentional prioritisation.

Interestingly in the sub-experiments they investigated the notion of increased facilitation when both hands were present. They illustrated that when both the participants hands were placed next to stimuli that appeared between them, the graded nature of the effect disappeared, likely due to both hands creating a facilitation for each target nearest them. To investigate this further, they looked at the contribution from each hand and whether this differed. In right handed individuals only their dominant hand created a significant NHE, supporting previous research (Lloyd, Azañón, & Poliakoff, 2010), but also found evidence to suggest that when both hands are present there is a non-linear increase in performance. The results of this study are important in regard to why any facilitation or change in processing near the hands might occur. The fact that the dominant hand sees the largest change would support the idea that this change in processing occurs based on action-planning. The additive response created with both hands may also be related to action-planning in cases where two hands are needed. If this is the case it could be tested with stimuli that possess different properties such as size and detail which may increase difficulty in successfully interacting with the object.

Attending to the environment can be overwhelming due to the vast amount of sensory information available, therefore in order to focus on what is important it is thought that we are able to select relevant information through filters or multiple levels of attentional processing (Kastner & Pinsk, 2004). The idea that attention can be manipulated

based on actions has been previously demonstrated. For example, Tipper, Lortie and Baylis (1992) illustrated that attentional interference can originate from action rather than perspective. Participants had to reach to lights within a workspace and ignore distractor yellow lights. The yellow lights caused more interference in the task when they appeared near the participants hand than any particular spatial location within the workspace. Reed et al (2006) argued that this was evidence that action-centred reference frames highly influenced attention and further suggested that in their study hand proximity facilitated target detection by prioritising attention. The following sections break down two key theories in efforts to explain the existence of the NHE.

### **The Bimodal Neuron Hypothesis**

The original experiment by Reed et al. (2006) cited research investigating bimodal visual-tactile neurons as the basis for their hypotheses. Single cell unit recordings from Macaques had shown groups of neurons that responded equally to tactile stimulation of the hand as to visual stimuli presented very close to the hand (Graziano & Gross, 1993; Graziano, 1999). These neurons have been shown to have tRF's on the hand and vRF's that extend beyond the hand in to the peri-personal space and were found in the putamen, parietal area 7b, intraparietal area, and inferior premotor area 6. The same neurons also responded to visual stimuli presented at graded distances from the hand which gradually saw a reduction in rate of action potentials suggesting a graded response in terms of distance. Since a graded response was also observed in experiments by Reed et al. (2006) this would suggest based on their properties that bimodal neurons do play a role in the NHE.

Graziano and Gross (1993) also illustrated differences in direction of movement of the stimuli, highlighting stronger neuron responses for stimuli moving towards the body than moving away. This could support the argument that the purpose of bimodal visual-tactile neurons is to aid in threat detection and give reason as to why items may undergo further evaluation. It would stand to reason that items approaching the body

could pose a higher threat and are higher priority for perceptual processing.

An important feature of bimodal neurons is that they are somatotopically organised. The vRF's have been shown to move with the hand and arm rather than being based on retinal centric co-ordinates. Therefore bimodal neurons are said to create a map of peri-personal space by combining sensory information regarding limb and eye positioning, and visual and tactile information creating a body-centred reference frame that updated in real time. This was shown through visual stimuli being presented in the space around the monkey's hand as the hand was moved to different locations. The same neuron showed active responses regardless of where the hand was positioned in space (Graziano & Gross, 1993). Bimodal neurons responded differently to purely visual neurons, which did not show a graded response depending on the distance of the stimuli. Furthermore, in human neurological case studies similar examples have been observed in which hand presence has altered perceptions. For example, Patient W.M. who had suffered a stroke affecting the occipital lobe resulting in significant impairment in viewing objects in the left visual field. With his left arm placed in the impaired visual field he was able to detect objects near the hand, doubling his ability (Schendel & Robertson, 2004). This improvement as a result of hand presence sounds very similar to the characteristics of bimodal neurons. The authors concluded that these findings further support the notion that arm position can modulate visual processing, this time in humans.

Follow-up work by Graziano (1999) investigated the relative role of both sensory inputs, vision and proprioception regarding the hand. If bimodal neurons move with the hand is this how limb position is encoded? Previous work has shown that the perceived location of the arm can be highly influenced by visual information. For example, the use of prisms to distort visual information about the arm resulted in changes to the perceived location as seen through pointing errors (Rossetti, Desmurget, & Prablanc, 1995). Similarly, viewing a rubber hand whilst it receives synchronous tactile and visual stimulation with their unseen real hand,

known more commonly as the Rubber Hand Illusion (RHI) can elicit feelings of ownership over the rubber hand (Botvinick & Cohen, 1998; Makin, Holmes, & Ehrsson, 2008). These examples highlight that even fake limbs can influence perceived hand location, therefore Graziano wanted to know whether a fake limb might also be influencing bimodal neurons.

To investigate this they used a stuffed monkey arm, the same species as the specimen used as the participant, and placed it in view of the monkey and in line with their real, covered, arm. They then manipulated the position of the stuffed arm whilst the real arm remained stationary and unseen. It was suggested that due to the conflicting proprioceptive information from the real arm this might nullify results and not show a shift in vRF's as a result of the moving fake arm. Alternatively if visual information is highly influential then a shift in the RF's would be observed, likely resulting in the perceived arm location as being between the two hands, as previously reported in illusion studies (Bellan et al., 2015; Ratcliffe & Newport, 2016). Results showed the vRF's did shift in the direction of the fake arm, despite the conflict between real and fake arm inputs.

In addition to testing a fake limb, they also re-tested findings by Graziano and Gross (1993) and confirmed that as the real arm was shifted the vRF's remained anchored to the tRF's. Furthermore, in the arm covered condition in which all visual information regarding the limb was removed, they observed a reduction in the amount that the vRF moved concluding sight of the arm was a contributing factor. Interestingly, the results also reported that not all neurons had a vRF that moved with the arm, however these variations in amount of shift could perhaps be accounted for by their positioning on the arm i.e. neurons with tRF's higher up the arm would consequently shift less as the arm is moved. The fake arm condition saw a larger shift than the arm covered condition, however less of a shift than when both congruent visual and proprioceptive information was available.

In addition, they reported curious observations for two neurons, specifically the RF's moved more when vision of the real limb was removed than when it was visible. In fact a reduction in the amount of shift was observed when they were able to view the limb. The author suggested that the neurons more strongly represented proprioceptive inputs and opposed visual information. When the fake arm was moved they observed that for these two neurons the RF's shifted in the opposite direction. It was argued that this was evidence of the fake arm "mimicking the visual effect of the real arm" (Graziano, 1999). In other words, as the fake arm moved further away from the real arm location the neurons compensated to indicate the relative position of the real arm. This could be an underlying mechanism that helps support the body schema by highlighting incongruences between visual and proprioceptive inputs.

What remains unclear from this evidence is whether or not the monkey was fooled into believing the stuffed arm was part of his own body. Is it important to take ownership over the fake limb, or is the visual input of something resembling our own effector enough? Research by Graziano, Cooke and Taylor (2000) demonstrated that a white piece of paper the same size as the fake arm did not elicit similar shifts in the RF's of the neurons highlighting the importance of appearance or the quality of the visual information in influencing the bimodal neurons. Furthermore they tested the fake arm in various orientations, realistic and unrealistic, and found that only the fake arm positioned in a plausible location affected the shift in RF's. This evidence clearly shows that for a fake limb to cause a shift in the vRF's it must resemble the real limb (but to what extent is not currently clear) and be in an anatomically plausible position. Due to the nature of the non-hand like fake limb being as simple as a white sheet of paper it is unclear whether it is the form of the hand that is important or the level of detail and realism. These factors would likely link to embodiment of the limb and indicate whether perceived ownership is critical to the effect.

With hand presence being a focus of further investigation, variations in stimuli and design added new evidence to this growing body of research

sometimes highlighting contradictory findings. This led to the original theory of how a near hand facilitation might occur to come under scrutiny and the development of new theories to emerge.

Goodhew, Edwards, Ferber and Pratt (2015) argued that Reed et al.'s attention prioritisation theory and Abram et al.'s theory of more detailed evaluation contradicted one another. The former suggests quicker reaction times, while the latter observed slower. However these do not entirely oppose one another but both show that items near the hand are processed differently to those in far hand space. If slower search times were observed due to detailed evaluation of each stimuli before moving on to the next then this could highlight two stages of visual processing. First a priority given to items in peri-personal space, as seen by the facilitated reaction times by Reed, and second a more detailed evaluation likely to determine use or threat. Therefore these pieces of evidence may not entirely contradict each other but give us more information eluding to the underlying mechanisms. On the other hand it has been suggested that due to the instability of these theories another may offer a more convincing explanation.

The examples so far have illustrated an enhancement in spatial processing to stimuli presented near the hands. Spatial processing is also important for reading in terms of being able to keep track of where you are on the page and in the sequencing of letters within a word (Stein, 2003). However reading also requires semantic processing, therefore research was undertaken to establish how hand proximity affected reading (Davoli et al., 2010). Three hypotheses were stated: either semantic processing, like spatial, would be increased; second semantic processing would be reduced at the cost of improved spatial processing; and thirdly that no change in semantic processing would be found.

Two tasks were used, one asked participants to judge the sensibleness of sentences, the other was a Stroop task. These tasks were completed with hands either in close proximity to the stimuli appearing on the screen or in their laps. Despite previously shown spatial enhancements near the

hands, semantic processing appeared to worsen with the hands close to the stimuli. In the stroop task reduced interference was shown in the proximal hands condition suggesting either reduced semantic processing or an enhancement of colour processing which in turn reduced the interference of the word meaning.

Conversely, another study using letters found benefits of hand proximity. However identification was all that was required, not semantic processing. Adam, Bovend'Eerdt, van Dooren, Fischer and Pratt (2012) used a letter identification task to help further evaluate the bimodal neuron hypothesis by testing stationary hands against the effects of moving hands. They hypothesised that the effects of hand proximity should be present in both the moving as well as the static hand conditions due to the real time nature of bimodal neurons in updating hand location. In the study participants placed their hands on sliding pads fixed to a rail beneath the horizontally placed monitor on which the letters appeared. Participants moved their hands inwards and outwards continuously for the moving condition with near, intermediate or far stimuli being categorised after the experiment. They were tasked with identifying as many letters as possible from the display which appeared for different durations (all 80ms or under). A further task with increased difficulty was also tested using 6 letters rather than 3. Results from both experiments showed no differences in accuracy between hands moving and static conditions, suggesting real time updating of limb position. Additionally they showed a graded effect of hand proximity, with the closest conditions showing greatest accuracy. It was concluded that hand proximity improves perceptual encoding processes, similar to findings by Abrams et al., (2008). The results were used to add support for the bimodal neuron hypothesis due to the graded distance effect. However, another conclusion was that the results suggest a link between perception and action, which could relate to bimodal neurons but also suggest support for another theory.



### **The Magnocellular Account**

An alternative account that could explain how near hand items receive facilitatory processing is the Magnocellular Account (otherwise known as m-cell account). This is based on the principle that there are two visual pathways primarily composed of two cell types: magnocellular neurons (m-cells) and parvocellular neurons (p-cells). These cell types have different properties that make them adept at different things. For example, m-cells have greater temporal sensitivity compared to p-cells which makes them superior at detecting rapid changes in luminance (Derrington & Lennie, 1984; Goodhew et al., 2015). They have faster speeds of conduction and if recruited could allow a person to respond faster to the onset of target appearances. P-cells on the other hand have higher spatial acuity due to their larger receptive fields meaning they are better able to detect changes in space. Due to these properties p-cells process detailed object features as well as colour, while m-cells encode temporal information such as motion and location (Maunsell, Nealey, & DePriest, 1990). M- and p-cells are thought to reside predominately in dorsal and ventral processing streams, respectively (Livingstone & Hubel, 1988; Merigan & Maunsell, 1993). Both streams contribute to the perception of stimuli, however one may be recruited more for particular tasks.

The difference observed between near and far targets, or items not within graspable space, even if relatively small distances apart indicate not just an enhancement for near hand items but a trade-off - between m- and p-cell processes. This increase in temporal acuity arises at the relative cost in spatial acuity that p-cells specialise in. Abrams and Weidler (2014) investigated this further by having participants discriminate between low and high frequency stimuli. They reported results consistent with m-cell processing showing participants were better able to discriminate low spatial frequency stimuli in the hands proximal condition. Furthermore they reported greater sensitivity to higher spatial frequencies with the hands away from the target suggesting a trade-off between m- and p-cell processing. When the hands are proximal to the stimuli m-cells have priority over p-cells creating these changes in discrimination ability.

Based on the notion that items near the hand are candidates for action, Gozli, West and Pratt (2012) theorised that the magnocellular visual pathway would be biased towards vision near the hands due to its action-oriented nature. With m- and p-cells being primarily divided into ventral and dorsal streams they consequently can be associated with either vision for action or visual perception, with the dorsal stream being heavily associated with reaching and grasping (Jackson, Jones, Newport, & Pritchard, 1997). To test this theory they used a gap detection task that had both temporal and spatial features and has been shown to differentiate between the two cell functions (Bocanegra & Zeelenberg, 2011). They hypothesised that with hands placed next to the stimuli this would enhance m-cell processing and increase performance on a temporal gap detection task, due to higher temporal acuity as a property of m-cells. Furthermore a decrease in performance was expected on the spatial gap detection task due to p-cells not being recruited with the hands near-by. As predicted their results showed that hand proximity improved performance on a task requiring high temporal resolution while performance decreased on the task requiring high spatial resolution.

This evidence gives a new perspective on how the NHE works by supporting the notion that objects in peri-personal space (graspable space) are candidates for action which biases the dorsal (action) pathway. By showing improvement on a temporal task the research highlights the likely enhancement of the m-cell pathway due to hand proximity. As a result the requirements of previous tasks become of vital importance in understanding the NHE.

First, in experiments which have observed decreases in reaction times to stimuli close to the hand it is possible that m-cells are responsible due to their ability to detect rapid changes in visual events (Stein, 2003). Therefore the sudden appearance of a target would be processed by m-cells. If we consider delayed disengagement observed by Abrams et al., it could be explained by the lower spatial sensitivity of m-cells. If presented with numerous distractor items rather than one target alone the relatively lower spatial acuity could impair their ability to distinguish individual

targets due to the high density. Furthermore a reduction in spatial processing would also impair reading ability as observed in semantic processing tasks (Davoli et al., 2010).

Research presented by Goodhew, Gozli, Ferber and Pratt (2013), also investigated differences in temporal acuity near the hands and demonstrated that hand proximity altered performance on an object substitution masking task. The task relies on an ability to temporally separate objects which improved with hand presence indicating again that stimuli near the hand benefit from enhanced temporal acuity, or in other words enhancement of m-cells.

Hand orientation, along with hand positioning, has been shown to alter the processing of visual stimuli nearby. Davoli and Brockmole (2012) had participants identify a central target letter with flanker letters on either side. Participants completed the task with either their hands away from the stimuli or placed them around the target letter. They reported that the hands appeared to shield attention from the distractor stimuli as demonstrated by participants being more accurate at identifying target letters only in the hand barrier condition. The other barrier condition that was not using the hands did not have the same effect suggesting the importance of the hand itself in creating this attentional barrier. A similar result highlighting the importance of the hand orientation showed faster reactions to targets appearing on the palm of the hand as oppose to the back (Brown, Morrissey, & Goodale, 2009). Furthermore, Weidler and Abrams (2013) tested hand proximity on a flat surface as oppose to raising the arms up to a screen as in many previous studies. They found that proximity to the hand was important, not the posture of the arm. These results highlight the functional aspect of nearby hands in that items presented on the palm side of the hand are more likely to be interacted with, perhaps representing the biasing of the action oriented m-cell pathway.

This action related effect has also been shown to exist in tool use. Participants responded faster to targets appearing on the functional side

of a rake rather than to the back of the rake (Reed, Betz, Garza, & Roberts, 2010). However prior to testing participants used the rake in a sand box meaning they may have embodied the tool which could have produced different results if they had not done this. These experiments implicate action planning and the functional properties of the hand/tool as reasons for the changes observed in visual processing near the hands.

However, what remains unclear is how the hand is able to cause this m-cell enhancement for items in close proximity. It is possible that bimodal neurons play a role by helping to localise the stimuli in hand-centred reference frames. Since the RF's move with the hand, creating a real time representation of peri-personal space, they could be responsible for detecting stimuli in graspable space which in turn primes that area as ready for action by biasing the m-cell pathway. Chan, Peterson, Barense and Pratt (2013) presented a similar argument suggesting it was near hand items that primed the brain ready for action and this in turn primed the m-cell pathway due to its involvement in fast object detection (Kveraga, Boshyan, & Bar, 2007). To investigate this they tested participants with their hands in different postures including palms-in (primed for action) vs back of the hand. They found that participants had an advantage in identification of low spatial frequency images only when the palms were facing towards the stimuli. This would suggest that stimuli in actionable space are processed differently. This highlights another difference between items near the hand indicating the importance of orientation.

### **Summary**

Attentional prioritisation suggested by Reed et al. (2006), nor detailed evaluation theory (Abrams et al. 2008) fits with the results put forth by Gozli et al., (2012) or Abrams and Weidler (2013) and therefore would imply that the more recent m-cell account is the most credible explanation for the changes in processing of stimuli near the hands. Arguably these changes occur due to biasing m-cells in the action (dorsal) pathway as a result of stimuli near the hand priming us ready to take action. This has been demonstrated by differences in visual processing not only near the

hand but differences in the orientation of the hand with palm sided targets receiving further facilitation (Davoli & Brockmole, 2012).

However, the m-cell account does not necessarily nullify the role of bimodal neurons. By combining visual and tactile information from near the hand bimodal neurons may play a critical role in updating hand location and localising the stimuli in peri-personal space. In turn this information could be responsible for enhancing m-cells in this region of space. Goodhew et al., (2015) argue that to fully explain the changes in processing around the hand both the bimodal neuron theory and the m-cell account need to be combined to form a more complete understanding of the effect.

More recently, contradictory research has come to light suggesting that hand proximity in addition to task demands alter which visual processing stream is biased. Goodhew and Clarke (2016) aimed to further examine the differences observed in near hand tasks, specifically relating to longer visual search times in scenes with multiple distractors. Remarkably they found a high spatial frequency advantage (attributed to p-cells) when the hand was placed next to a visual search paradigm. This research implies that task demands influence any effect of hand proximity. For example, when spatial task demands are small (few targets) m-cell processing receives a boost, whereas when a scene would benefit from higher spatial processing p-cells are primed. The question remains, how are these pathways biased? Perhaps items encoded as within peri-personal space also encode the density of stimuli nearby and this helps decide what pathway to prioritise. Regardless, this evidence shows that m- and p-cell processing is not fixed, but can change depending on task demands.

A task measuring the NHE may therefore provide a way to monitor any changes in the processing of peri-personal space that may be influenced by temporal, spatial, or fidelity changes to the hand.

## Conclusions and Research Aims

With evidence showing the plasticity of peri-personal space and the sensory discrepancies present in VR systems, this thesis aimed to explore how peri-personal space might be altered as a result of these discrepancies. Furthermore could tDCS modulate any observed changes in order to overcome them? Therefore a series of experiments were devised to investigate temporal, spatial, and fidelity changes, along with the application of tDCS. Additionally, the research presented here could highlight what VR factors are the most detrimental to performance, allowing future developments to prioritise a particular aspect.

First, it was hypothesised that spatially separating the visual and proprioceptive sensory inputs would change how near and far targets were responded to, either through possibly expanding the region of space, or the shifting of bimodal neurons. Second, could tDCS to the PPC alter how peri-personal space is processed as the sensory inputs were separated?

In terms of fidelity changes, it was hypothesised that reducing the realism of the hand could lower the effectiveness of the NHE, perhaps nullifying it. This would be investigated with spatial inputs congruent, something that has not previously been investigated.

It was also hypothesised that temporal lag added to the augmented hand would reduce the NHE as a result of incongruent sensory information received from completing a reaching task. Furthermore, movement times and accuracy would be impaired as a result of the added lag.

## Chapter 2 Pilot

Previous research has established a reliable NHE using a real hand, along with a diminished, yet observable, NHE with both visual and proprioceptive inputs separately, using a rubber hand after being embodied by the participant and a covered real hand (Reed, Grubb & Steele, 2006). Whether an NHE is still present within a virtual/augmented environment using a representation of the hand has not been tested. As highlighted in chapter 1, sensory information may be subject to delays, or other confounds in an augmented environment that are not present in the real world. These changes in sensory input could influence the representation of the body, and in turn peri-personal space. Therefore it is reasonable to assume that changes in the way sensory information is perceived may alter how, or where, we process things around us. This experiment was designed to firstly establish whether a basic NHE exists in this environment, using the MIRAGE, and secondly to demonstrate whether the effect is abolished when the hand is replaced with an arbitrary visual anchor.

The MIRAGE mediate reality system (see methods for full description) allows each participant to view, and take ownership over, a visual representation of their hand that is a live video recording of their limb. By appearing in the same physical location as their actual hand participants have a high degree of ownership over the limb allowing a more realistic approach than the use of a rubber hand. MIRAGE permits the overlaying of targets that appear digitally within the MIRAGE workspace, meaning targets appear directly in line with the hand of each participant, and therefore creates an augmented environment. Therefore targets and the hand are all within the augmented environment and allow us to test whether a reliable NHE is observed in this setting, with no additional manipulations. This stage was referred to as 'BASE' indicating a baseline measure of the NHE within the MIRAGE.

Second, it was important to establish that an arbitrary visual anchor within the environment does not produce the same effect, as this could indicate the effect is not related to the hand specifically, but occurs due to the additional visual information. Therefore one stage involved participants responding to targets appearing near and far from a block placed within the MIRAGE while their hands were placed at their sides, this stage was referred to as 'BLOCK'. It was possible that any facilitation observed for a near target could be due to proximity to the trunk/body as different extensions of peri-personal space have been observed from different areas of the body. In particular the visual receptive fields extending from the head has been shown to be up to 1 metre (Graziano & Gross, 1993).

A third stage of the experiment was designed to test purely the proprioceptive component of the NHE in which participants did not have vision of their hand, nor did they see a virtual representation (this stage was referred to as 'PROP'). This was necessary to confirm previous findings that proprioception should also elicit an NHE without the presence of any visual information. Additionally this stage was important to allow a comparison between a hidden hand condition, and the unseen hand in 'SEP' in which it is competing with additional visual information (see below).

The final stage of the experiment was designed to establish if a spatial separation between the seen and actual hand (10cm) would alter the NHE. Based on previous research that has shown that visual and proprioceptive inputs contribute to creating an NHE (Reed et al, 2006; Abrams, Davoli, Du, Knapp & Paull, 2008; Graziano, 1999) this stage of the experiment was designed to test if this could be achieved within an augmented environment, and second would both inputs create an equally strong NHE or would vision be dominant (Congedo et al., 2006). When these inputs have been tested previously in humans, examining the NHE, they have always been tested separately, (i.e. the real hand remains in the participants lap, untested, while a fake visual hand is examined) however by using the MIRAGE to spatially separate the two hands (visual/virtual



and proprioceptive/real) it will be possible to test them concurrently. This stage is referred to as 'SEP' indicating visual and proprioceptive inputs have been separated.

For BASE it was hypothesised that an NHE would be shown within the augmented setting as both visual and proprioceptive inputs are aligned and should therefore not cause any changes to the hand representation. Theories explaining the NHE rely on the brain having a stable representation of the hand, which should remain established as no manipulation is occurring using the MIRAGE (Tseng, Bridgeman & Juan, 2012). Therefore it was expected that near targets would be responded to faster than far targets.

Second, in the BLOCK condition it was hypothesised that no difference between near and far targets would be shown as a block should not create the same facilitation benefits that the hand does. Therefore reaction times to all targets should not differ.

Third, it was hypothesised that the hidden hand in the PROP condition would elicit an NHE, but be less significant than BASE in which both visual and proprioceptive inputs can be utilised, replicating conclusions by Reed et al that separate inputs created a less reliable NHE. These conditions were statistically compared.

For the SEP condition it is hypothesised that an NHE would be observed for each hand, potentially due to an expansion of peri-personal space, as observed in tool use (Holmes et al. 2004). Furthermore, it was hypothesised that any effect observed would be less reliable than any observed in the BASE condition as the visual and proprioceptive inputs are separated and not responding optimally as they would together. It was also expected that the visual hand would have a larger difference between near and far targets than the proprioceptive hand due to visual information often being dominant (Touzalin-Chretien, Ehrler & Dufour, 2010). It was also feasible that PROP will present a stronger NHE than the proprioceptive hand in the SEP condition as it did not have to compete with incongruent visual information about the location of the hand. The

presence of competing visual information could influence the reliability of the NHE for the real hand.

## Methods

### Design

BASE, BLOCK, and PROP all compared the reaction times to targets that were presented in two locations, near (~2cm) and far (~15cm) from the tip of the middle finger of the hand (or block). BASE compared reaction times with the right hand presented within MIRAGE. For BLOCK the hand was replaced with a rectangular block that was approximately the same dimensions as a hand (15 x 10cm) (Abdel, Ibrahim, Khalifa, Hagrass, & Alwakid, 2016). PROP also involved placing the right hand within the MIRAGE, however the participant was unable to see the hand. SEP was a 2 x 2 design with hand modality (2 levels; visual and proprioceptive) and target distance (2 levels; near and far) as the independent variables. Reaction time (ms) was the dependent variable for all 4 conditions, recorded via a foot-pedal response.

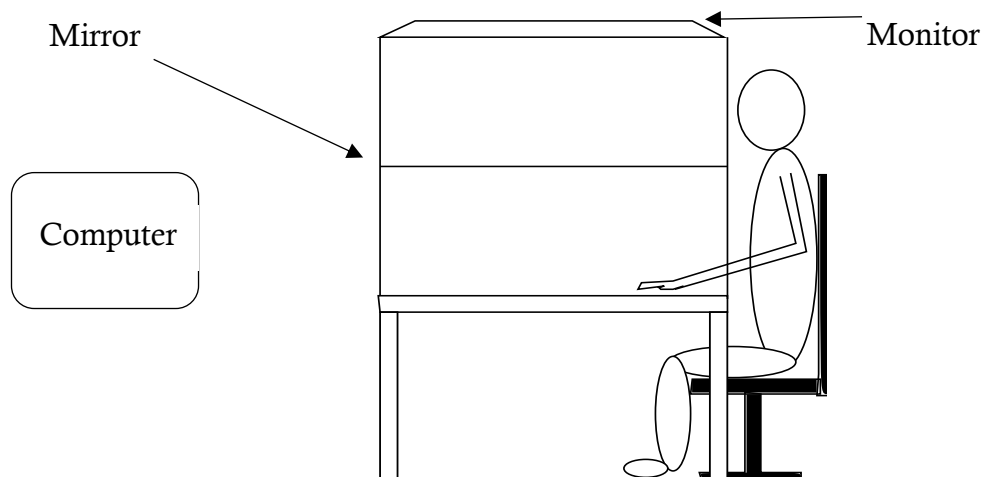
### Participants

Fourteen participants were recruited from the University of Nottingham, 6 were male. Ages ranged from 20-28 ( $M=23$ ,  $SD = 1.5$ ). All participants were from the Department of Psychology. All participants were right handed, as assessed through the Edinburgh Handedness Questionnaire (Oldfield, 1971) (Appendix 1). Minimum age for recruitment was 18. Participants above the age of 39 were not recruited as this has been shown to be the peak age before myelin starts to decline in the brain which is vital for synaptic transmission meaning that cognitive, sensory, and motor processing speeds will decline (Bartzkis, 2010).

Research looking at gender difference when embodying a virtual body has shown that males and females are equally able to embody a virtual body or a body part belonging to another person (through use of head-mounted displays in which they are able to look down and view another person's body in place of their own) even if the new body is a different gender (Petkova & Ehrsson, 2008). Therefore it was not vital for an equal number of males and females to be recruited.

## MIRAGE

Stimuli were all presented within the MIRAGE. The MIRAGE is a mediated reality system with the ability to augment, and alters perception of the body in real-time, as well as having the ability to impose digital stimuli within the environment. The MIRAGE takes real input (i.e. a hand) and creates a real-time virtual output that can be manipulated in various ways, including temporally, spatially, and visually. Participants view a live video feed of their own hand in the same spatial location as their real hand using a system of cameras and mirrors. The real-time feedback, with a lag of 10ms/frame, allows participants to embody the virtual hand by gaining a sense of agency through movement. See Figure 2-1 below for illustration of MIRAGE set-up.



*Figure 2-1:* Diagram representing the MIRAGE. Participant is seated directly in front of MIRAGE and places hand inside. They look down at a mirror and see their hand in the correct location. Distance between monitor and mirror is the same as the distance between the mirror and the hand.

As illustrated by Figure 2-1 participants viewed the virtual hand via a horizontally placed mirror that reflected the recording of the hand being displayed on the monitor (which faced down onto the mirror). The distances between the hand, mirror, and monitor were equal, allowing the virtual hand to appear in the same location as the real hand. This set-up

meant that participants may have been unaware that they were looking in to a mirror as they perceived the hand where they expected.

As illustrated in Figure 2-2 below, the participants viewed their hand in its veridical location inside MIRAGE and therefore may have gained immediate ownership over the virtual limb, without the need for additional tactile feedback such as stroking that is used for rubber hand illusions. The workspace within MIRAGE measured 720mm x 490mm.



*Figure 2-2:* Image of the MIRAGE showing participant placing right hand inside. Virtual hand is viewable in its veridical location through the mirror.

### **Stimuli**

Targets were red circles measuring 7.92mm in diameter. A green fixation cross was always presented centrally between all possible target locations, i.e. when four target locations were possible (SEP condition) the fixation cross was in the centre of these possible locations, which differs to when only two targets are present, with the cross remaining in line with their middle finger. The presence of the fixation cross was to ensure that the hand did not act as a visual distractor, biasing responses near the hand.

Targets appeared in line with the participant's middle finger, distally rather than horizontally.

The distance of the far stimuli was ~15cm from the tip of the participant's finger, as this was close to the upper limit of the MIRAGE workspace, and the furthest they could be placed, when taking in to account the varying sizes of the hands of participants. The distance of the near stimuli was chosen to be ~2cm from the edge of the finger tips. The distance between the two targets was always 13cm. (See Figure 2-3).

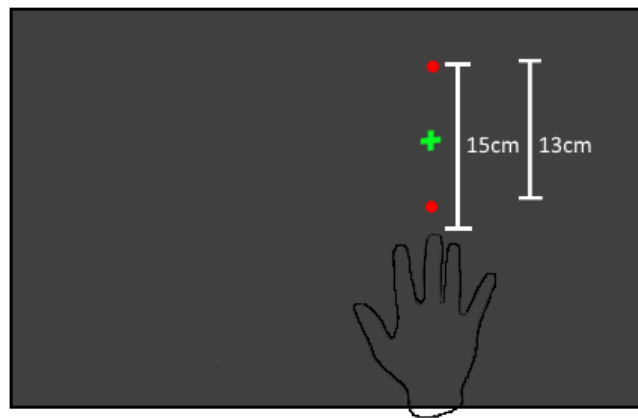


Figure 2-3: Diagram illustrating target positions relative to the participant's hand inside the MIRAGE workspace. Targets would appear one at a time, while the fixation cross remained visible throughout. 13cm was the distance between the two targets.

In some previous research the near targets had been placed on the back or palm of the hand (Brown, Morrissey & Goodale, 2009), however this method was not selected as it would result in participants focusing on the hand more and could act as an anchor. Furthermore, differences between the palm and the back of the hand have been shown, specifically that targets appearing on the palm may take advantage of higher tactile receptive field density that creates a stronger facilitation (Chan et al., 2013). Therefore it would be logical to test the palm side of the hand if placing targets on the hand itself, however having participants place their hands palms-up within the MIRAGE could be uncomfortable for the duration of the tasks. Particularly in later experiments where the hand would need to be held up rather than relaxed on the surface. Therefore it

was decided to use the palms-down position for consistency across experiments and place the near target 2cm from the tip of their middle finger. Additionally the NHE has been shown to be a graded effect, i.e. the closer stimuli are to the hand, the stronger the facilitation (Tseng, Bridgeman & Juan, 2012). Therefore targets appearing 2cm from the hand should still display a relative facilitation over targets presented at 15cm, even if they are not in direct contact with the hand.

The hand sized block was a cardboard box, 15 x 10cm, and was wrapped in white plain paper. This was approximately the same size as the average participant's hand and therefore targets appearing 2cm from the tip of it would be in approximately the same location as they would be for the hand conditions (and therefore the same distance away from the body). Target appearance and location was manually initiated by the experimenter meaning hand size was compensated for, and the distance from the block was always consistent. Targets appeared pseudo-randomly for a maximum of 2500ms but would disappear as soon as the participant responded. After the removal of a target the next one would appear between 1000 and 1500ms later.

### **Procedure**

#### **'BASE'**

Participants placed their right hand inside the MIRAGE and viewed it through the mirror so it appeared in the same location as their real hand but they were viewing the live video feed/virtual hand. Their hand was kept stationary for the duration of the trials. A small plastic marker was attached to the edge of the MIRAGE as a tactile cue for participants to line up their hand to ensure hand position was consistent across subjects. Participants were asked to keep their gaze on the fixation cross, which appeared for the duration, and was presented centrally between the two possible target locations. Participants were instructed to press the foot-pedal as fast as possible whenever they saw a target appear. Targets appeared pseudo-randomly in either the near or far location and were presented for 2500ms or until the participant initiated the foot-pedal

response. The interval time between targets was randomised to be between 1000 and 1500ms. This randomisation was to avoid participants being able to make anticipatory responses. A total of 80 targets were presented, 40 near and 40 far.

#### ‘BLOCK’

Participants completed the same task again but this time their hands were placed at their sides or behind them, and a block was positioned within the MIRAGE in the same location as the hand had previously been. Participants responded to another 80 targets using the foot-pedal response.

#### ‘PROP’

For the PROP condition participants had their right hand placed within the MIRAGE however this time the image of their hand was not displayed. During this condition the hand was still physically in line with the targets appearing within MIRAGE, but the participant was unable to see a hand. Again, participants responded to 80 targets.

#### ‘SEP’

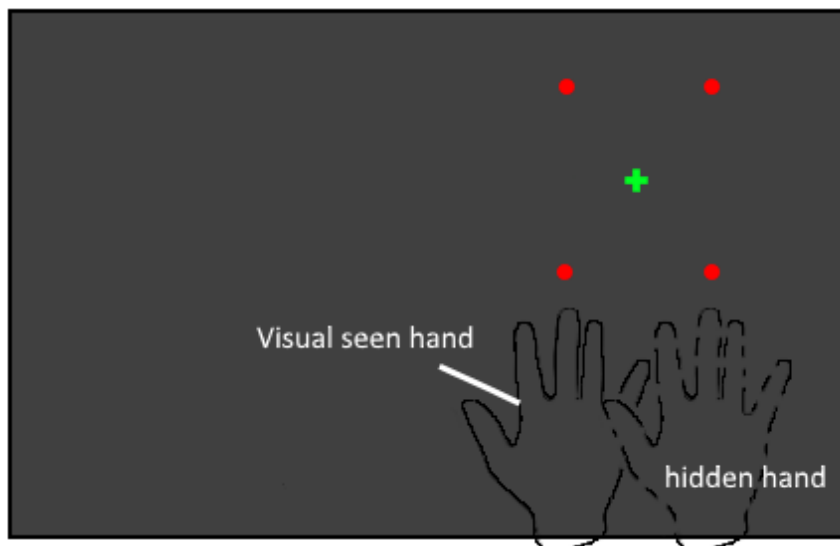


Figure 2-4: Illustration to show SEP condition in which the real hidden hand is positioned to the right, while the visual hand can be seen on the left. Targets appeared in line with both.



For this stage participants first viewed their right hand in its veridical location, and then saw a brief black screen before the hand reappeared but displaced 10cm to the left. Participants were aware of the displacement. Targets were pseudo-randomised to appear in one of four locations, near or far from the visual (virtual) hand, and near or far from the real (proprioceptive) hand location (see Figure 2-4). 40 targets appeared in each of the possible locations resulting in a total of 160 target reaction times.

Order of conditions was counterbalanced across participants. Each stage lasted approximately 2 minutes, however SEP lasted 4 minutes due to increased number of targets.

## Results

### Outlier Removal

Reaction time data poses a problem for analysis in that it is almost always positively skewed with a long right tail and often contains numerous outliers. Outliers refer to lapses in concentration, anticipatory responses, or indecision, rather than extreme data points that may result from experimental manipulation. But separating genuine outliers from those that do result from the experimental manipulation is almost impossible; therefore the most practised solution is to remove the extreme data points whilst trying to retain a high percentage of the dataset. There are numerous methods to achieve this including using absolute cut-offs, standard deviations, or data transformations.

Ratcliff (1993) investigated the effects of different outlier removal methods, showing that power varied between methods but not the number of type I errors. Specific cut-offs appeared to have the biggest increase in power, followed by data transformations.

Data transformations, although useful in reducing skewness, are at risk of removing significant effects as they change the relationship between the variables, often by changing the intervals between them. The order of the data may be maintained but the intervals between each data point are changed due to the transformation, which in the case of ratio data such as reaction time, would become ordinal (Osbourne, 2002). So although transformations may aid in improving normality, the way in which they change the nature of the data could affect the way the data is interpreted and therefore poses significant issues.

Similarly, using  $2\pm$  SDs to remove potential outliers also creates changes in the data, namely reducing the variance and causing a problem if two experimental conditions created relatively different reaction times. This is why cut-offs need to eliminate only a certain proportion of the dataset to ensure valid trials are not being mistakenly removed as outliers. Ratcliff (1993) recommended the use of cut-offs as long as no more than 10-15% of the data is lost.

The reaction time data presented in this chapter has been trimmed using the +/- 2SD method to remove potential outliers and improve normality. This was done on a participant basis as there was more variability between participants than across conditions. Additionally each participant's data set was individually inspected to record the amount of trials removed to ensure total data loss was within the recommended range mentioned above. For the following data 6% of data were removed, including invalid trials (where the foot-pedal was not pressed at all within the time frame the target was displayed for).

### **Reaction Time Analysis**

#### **BASE**

To establish if a NHE existed within an augmented environment a paired samples t-test was carried out comparing the difference between near-hand and far-hand targets with the hand placed stationary within the MIRAGE. It showed a highly significant result,  $t(13) = -4.307$ ,  $p = .001$  illustrating that near targets ( $M=364.97$ ,  $SD=42.8$ ) were responded to faster than far targets ( $M=378.7$ ,  $SD=47.2$ ).

#### **BLOCK**

A paired samples t-test was run to analyse the difference between near and far targets when a block was placed within the MIRAGE, in place of a hand. The results showed no significant differences,  $t(13) = -.750$ ,  $p = .467$  between reaction times to near ( $M=378.94$ ,  $SD=50.04$ ) and far targets ( $M=382.94$ ,  $SD=41.26$ ).

#### **PROP**

For the invisible hand condition a paired samples t-test was also run and showed a significant difference,  $t(13) = -2.508$ ,  $p = .026$ , with near targets ( $M=362.63$ ,  $SD=27.7$ ) being responded to faster than far targets ( $M=376.21$ ,  $SD=31.45$ ) indicating that proprioception alone is sufficient to elicit a NHE.

#### **SEP**

The displaced condition was analysed as a 2 x 2 repeated measures ANOVA with hand modality (2 levels, visual and proprioceptive) and target distance (2 levels; near and far) as independent variables. The results showed a significant main effect of target distance,  $F(13) = 28.046$ ,  $p < .001$ , meaning that near targets ( $M=365.11$ ,  $SD=10.30$ ) were responded to significantly faster than far targets ( $M=381.74$ ,  $SD=12.07$ ). Additionally there was no significant difference between hand modalities,  $F(13) = 1.482$ ,  $p = .245$ , nor was there a significant interaction,  $F(13) = 1.576$ ,  $p = .231$ , suggesting that a NHE was created from both the visual and proprioceptive inputs individually. Post hoc t-tests showed both hand conditions generated a sufficiently significant NHE; visual hand  $F(13) = -3.300$ ,  $p = .006$ ; proprioceptive hand  $F(13) = -5.983$ ,  $p < .001$ .

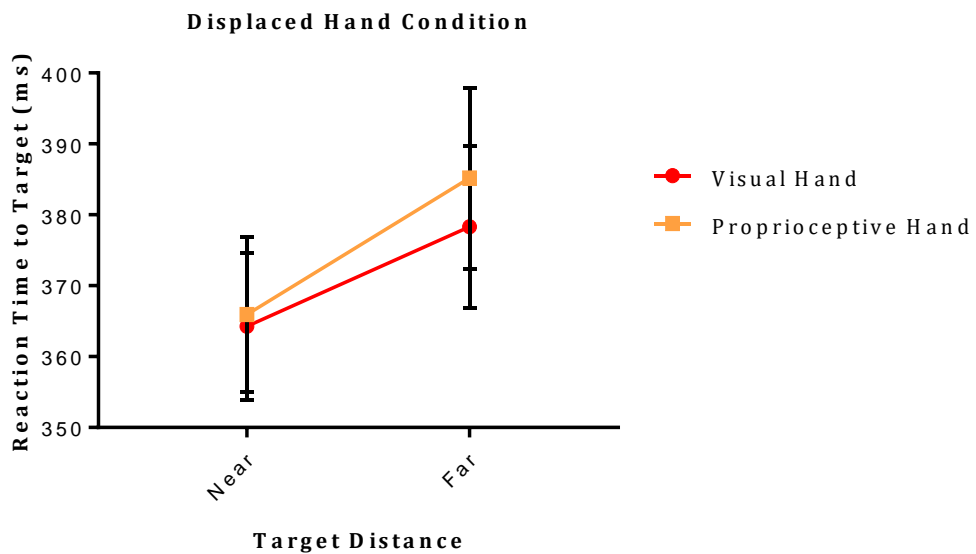


Figure 2-5: Graph displaying means and SEM for near and far targets for each hand modality. Both hands demonstrate a NHE with near targets eliciting faster reaction times.

Additionally, a paired samples t-test was run to compare near reaction times in the PROP condition, to near reaction times in the SEP for the proprioceptive hand. This comparison would indicate whether the visual hand in the displaced condition was creating an additional competing interest that in turn could diminish the NHE for the proprioceptive (unseen) hand in the SEP condition. The results of the t-test showed no

significant differences,  $t(13) = -.345$ ,  $p=.735$ , between the PROP ( $M=362.63$ ,  $SD=27.7$ ) and SEP ( $M=365.93$ ,  $SD=40.72$ ) hand conditions.

## Discussion

The results of the t-test for BASE clearly shows that a NHE can be established within an augmented environment as near targets elicited a highly significant facilitation effect over far targets. This supports the hypotheses and is in line with previous research that has shown a NHE with fake limbs after being embodied by the participant (Reed et al, 2006; Graziano, 1999; Makin, Holmes & Zahory, 2007). The virtual hand presented in MIRAGE had a higher fidelity than a rubber fake hand due to it being a live-video recording of the participants own hand, and could therefore be considered a middle-ground between a real hand and the embodiment of a fake hand. Additionally in the present set-up the virtual hand was tested whilst the proprioceptive inputs were congruent, a set-up that has not previously been tested. Therefore it was most likely the combination of fidelity and congruent visual and proprioceptive information that resulted in a significant NHE being observed for the virtual hand. This study confirms the previous findings first reported by Reed et al. (2006) and does indeed suggest a facilitation for items near the hand over items further away.

It was also important to confirm that this facilitation was not due to the visual presence of the hand, acting as a distractor. It was possible that any facilitation observed was simply the result of biasing of attention by the presence of any additional visual information. However, in line with previous research that it is the presence of the hand that is important, not an arbitrary visual anchor (Reed et al., 2006; Davoli & Brockmole, 2012) the results of the block condition did not show a significant NHE. The block, which was approximately the same dimensions as a hand, and placed in the same location in line with the targets, did not cause a significant facilitatory effect. This is in line with our predictions and suggests that it is the presence of the hand that must affect the processing (and perhaps prioritisation) of space, not simply a visual effect causing any shifting of attention. A recent study that looked at positioning of the hand as a barrier around target letters in a flanker task, demonstrated that it was only the hand that was effective at blocking out distractors by

enhancing attention towards the side of space that the palm was facing. When an arbitrary barrier was used, this effect was not observed, again suggesting that the hand itself is responsible for any facilitation due to mechanisms not fully understood (Davoli & Brockmole, 2012).

To further understand how the NHE works, the visual and proprioceptive inputs needed to be examined in order to be able to evaluate the proposed theories behind how the effect is created. The PROP condition tested purely the contribution of proprioception by having participants complete the task with the absence of vision of their hand. The results of the t-test showed that a significant NHE was still created, although not as strongly significant as the congruent hand condition in BASE. This is in-line with the hypothesis and past research (Reed et al., 2006; Abrams et al., 2008) that proprioception alone would be enough to elicit a NHE but additionally that it would be weaker than when combined with a visual contribution.

It could be suggested that this result is due to the amount of cross-modal interaction of highly connected visual-tactile regions in the brain that are responsible for coding peri-personal space (arm position, Graziano, 1999; peri-hand space, Makin, Holmes & Zahory, 2007; Dufour & Touzalin, 2008). Evidence from monkey literature has demonstrated that neurons that respond to both visual and proprioceptive information regarding arm position, with overlapping receptive fields, saw a response even when visual information was not available (Graziano, 1999). Therefore if visual and proprioceptive/tactile information is being received by the same set of bimodal neurons then visual stimuli presented near the invisible hand, and within the bimodal receptive fields, should create the same neuronal response. These receptive fields have been observed to move with the hand, rather than being retinal-centred.

The role of bimodal visual-tactile neurons has been argued to have evolved to aid in manual interactions such as reaching and grasping objects or tools (Brown et al., 2008). Specifically bimodal neurons may improve tactile and visual resolution (Graziano & Cooke, 2006). This

would be particularly useful for the hands and face regions in which tactile receptive fields are more densely populated. By recruiting both visual and tactile receptive fields the improved resolution would likely improve accuracy in reaching/grasping, possibly act as a threat detection system, or allow more detailed evaluation of objects for tool-use. In summary, PROP suggests that proprioceptive information alone is sufficient to cause a neuronal response to items within the peri-personal space, perhaps through recruiting bimodal visual-tactile neurons that detect a visual stimuli (the targets) within range of the vRFs of the unseen hand.

SEP was designed to directly test the contributions of visual and proprioception to the NHE by spatially separating the two inputs. Utilising MIRAGE programming, the virtual hand was displaced and presented 10cm to the left of the real hand location. Only one virtual hand was presented meaning the real hand was hidden. The results showed that both hand modalities established a significant NHE, in-line with previous research that both visual and proprioceptive inputs contribute. Additionally there was no main effect of hand modality suggesting both inputs created equally sufficient effects. This is not entirely supported by previous research which would suggest that the visual input may create a dominant effect (Touzalin-Chretien et al., 2010). Furthermore, imaging research has suggested that the representation of peri-hand space is driven by vision, while proprioception makes a lesser contribution (Makin, Holmes & Zohary, 2007). Therefore it was expected that the proprioceptive hand targets might show less of a facilitation, however this was not found. Later experiments investigating the effect of non-invasive brain stimulation will highlight if these contributions can be changed through stimulation to the posterior parietal cortex, the region responsible for the integration of sensory information in regard to peri-personal space (Serino, 2011).

Examining this effect in humans has not previously tested both sensory inputs separated, yet at the same time. Traditionally a rubber hand is embodied to test the visual input while the real hand is not presented with targets during the same set of trials, but is tested separately in a later



condition. Therefore it is possible that different results may be obtained if they were tested separately. The purpose of PROP was to allow a comparison between the two proprioceptive hands (from PROP and SEP) to evaluate if a competing resource (the virtual hand, present in SEP) had a confounding effect. The results of the t-test showed no differences in near target reaction times between the two proprioceptive hand conditions. However there does appear to be more variation in the displaced condition in which a virtual hand is also present. The results suggest that regardless of competing visual information, the proprioceptive contribution to the NHE remains stable.

Research by Graziano (1999) using Macaque's also tested the effect of stimuli approaching both a fake stuffed monkey arm alongside the real covered arm. They hypothesised that the visual receptive fields of bimodal visual-tactile neurons (which change based on arm-centred co-ordinates) would also move due to the presence of the stuffed arm due to vision of a fake limb being able to influence perceived arm location (Botvinik & Cohen, 1998). They found that these neurons moved in the same direction as the fake arm, even though the real hand remained stationary. In relation to the present study, this evidence would suggest that visual information from the virtual hand, and proprioceptive information from the real hand, converge on the same set of neurons and influence the representation of peri-personal space. What is unclear from these results is whether the representation of peri-personal space is expanding to include both hands (as observed in tool-use), or whether different visual receptive fields are processing the information and are not as efficient as when they are congruent. Notably these results suggest that even with a 10cm separation both hands are responding similarly to when they are together.

Another possibility is that a new representation of the hand is being created due to the incongruent sensory information creating a new perceived hand location. As mentioned previously, perceived hand location can be manipulated by changing the visual information about the hand. Research by Ratcliffe & Newport (2016) found that when using the

MIRAGE and displacing the hand, participants perceived their hand as being 60% of the distance towards the visual hand. If this is occurring in our set-up and the hand is perceived as being in neither the visual nor the real location, but somewhere in-between, then the visual receptive fields of the bimodal visual-tactile neurons may have shifted towards the visual hand location. This could explain why near visual and near proprioceptive hand targets still maintained an NHE as they were still utilising the receptive fields of these neurons. This shifting of receptive fields may of course have a spatial limit. Based on RHI research, limits of 30cm have been observed, after which point the arm embodiment ratings significantly decline (Lloyd, 2007). Due to limits of the MIRAGE workspace, larger separations are not currently possible, however in the future a larger separation may not be able to maintain a stable or observable NHE.

If a new representation of the hand is being created then the area around the perceived hand location could be benefiting from m-cell priming as well as the vRFs of bimodal neurons. From this experiment one theory can not be ruled out in favour of another, however both could play a role in creating the facilitation, particularly a biasing of the m-pathway due to no facilitation being observed in the block condition which could have been seen if bimodal neurons were solely responsible as they should also encode space extending from the body and head.

Subsequent experiments will address what might be happening as the hand is separating by having a covert adaptation that gradually moves the hands apart to evaluate targets at various points of the separation. This should allow us to create a picture of how the hand is being represented when sensory information is being manipulated. Additionally, further experiments will investigate how the processing of peri-personal space might change due to other factors including temporal lag on movements, and appearance changes to the hand.

### **Chapter 3 The Effect of Spatially Separating the Seen and Felt Hand Locations on Peri-personal Space.**

The results of the pilot experiment established that a reliable NHE can be created within the MIRAGE environment suggesting that when all sensory inputs are congruent (vision, proprioception and touch) the naturally occurring NHE is still observable. The present experiment was designed to investigate how the NHE, and peri-personal space, might be altered when proprioceptive information is not congruent with visual information created by a covert paradigm.

As seen in the pilot experiment, a spatial separation between the seen and felt hand locations of 10cm was unable to significantly degrade the NHE. However, this separation was explicit, and did not involve a steady separation but an immediate dislocation. This could influence the perceived location of the hand. Both the visual and proprioceptive hands were tested together and then separated. It is not clear from the pilot what would happen if the hands were gradually, and implicitly, separated. Observing a gradual separation would highlight what happens to peri-hand space during a separation.

In this experiment participants placed their hand in the MIRAGE hovering and were tasked with keeping it visible between two encroaching bars at all times, whilst at the same time responding to targets that appeared in line with a visual representation of their hand, and targets that were moving gradually rightward (and in line with their real unseen hand as it was covertly separated from the visual representation).

The whole notion of the NHE may rely on a stable body representation and that of peri-personal space. As previously mentioned in chapter 2 the perceived limb position is highly influenced by visual information (Botvinick & Cohen, 1998; Ehrsson, Spence, & Passingham, 2004), and this likely shifts the receptive fields of bimodal visual-tactile neurons, even using a fake limb (Graziano, 1999). Therefore maintaining a degree of ownership over the visual limbs is probably required. Some evidence has

shown that the representation of peri-hand space is not static, but can be influenced by visual information, even illusory, to mean that items in far hand space are processed as near due to the illusory visual input (Làdavas & Farnè, 2004).

Newport, Pearce and Preston (2010) suggested that the body schema can only support one limb at a time, whilst the body image can maintain multiple limbs. In the present study by covertly separating the hands two representations are created, the visual representation and the unseen real hand. By measuring the NHE for each hand, results could highlight whether it is retained for one, or both hands. Consequently this could indicate whether the NHE is reliant on the body image or body schema. The covert nature of the separation in this study could have had a different influence on the representation of the limb compared to the overt separation in the pilot.

The covert separation paradigm involves participants having to adjust the visual representation of their hand to keep it visible between two encroaching digital bars. This means both the visual and unseen hand are moving slightly. Previous research has demonstrated that receiving visual feedback of active movement can alter the perceived hand location, shifting it towards the visual hand (Tsakiris, Hesse, Boy, Haggard, & Fink, 2007). However, the adaptation in the current study meant that the scale of the movement was not reflected accurately to the participant and therefore may not have had the same impact. It is therefore unclear how this covert separation will affect the perceived hand location and what impact this might have on the NHE.

As mentioned in chapter 1, the m-cell account is one of the main theories that could explain a near hand facilitation. It postulates that m-cells facilitate the input from near hand space at the relative cost of p-cells. A key difference between m- and p-cells is temporal and spatial acuity with p-cells having superior spatial acuity, while m-cells have higher temporal acuity (Bush & Vecera, 2014; Denison, Vu, Yacoub, Feinberg, & Silver, 2014; Goodhew et al., 2013). With this in mind it was theorised that the

present task involving a spatial separation might help further evaluate this theory. For example, if far targets rely on p-cells (which have higher spatial acuity) and near targets rely more on m-cells (with lower spatial acuity) then a change to spatial properties may have more of an impact on far targets due to the relative heightened sensitivity of p-cells. Therefore if the spatial separation affects near and far targets in a different way then this could lend support to the m-cell account.

Furthermore, as m-cells are more temporally sensitive this should lead to decreased reaction times to stimuli near the hand due to the higher sensitivity to the abrupt onset of the stimuli. In other words, stimuli appearing near the hand which are already enhanced through m-cell prioritisation can be detected faster than stimuli not receiving the m-cell benefits. This should mean that near hand targets are responded to faster than far targets. Furthermore, the m-cell theory suggests that it is the vision of the hand that is responsible for biasing the action-oriented pathway (Gozli et al., 2012). Based on this assumption it can be expected that the visual hand would create a more reliable NHE.

Alternatively if bimodal neurons played a vital role then it was expected that we would see a gradual increase in reaction times as the hands separate. There are two explanations for this, firstly as supported by Reed et al (2006), when both inputs are available to the participant (i.e. when the hands were together at the beginning) the NHE should be more reliable than when the hands are separated. This would be expected to be shown by a smaller difference, or perhaps a loss of a significant difference, between the reaction times for near and far targets as the hands are separated. A result like this could support the bimodal neuron theory as the neurons respond more strongly when both visual and proprioceptive inputs are congruent.

Second, as the hands are separated a new representation of the hand location may be created, perhaps replacing any existing representation, 60% towards the visual hand (Ratcliffe & Newport, 2016). The receptive fields for the bimodal neurons should be shifted towards the visual hand

and away from the proprioceptive hand. In monkeys, the visual receptive fields have been shown to move in the direction of the visual hand, even when the real arm is stationary (Graziano, 1999). Therefore it was expected that near visual targets would be responded to faster than near proprioceptive targets (but slower than when both inputs are together). However research has also shown that not all neurons moved toward the visual hand, with some more active when vision of the hand was removed (Graziano, 1999). Therefore by dividing the neurons between the real and visual location this could be the cause of the less reliable NHE.

These changes to the NHE could illustrate changes in the representation of peri-personal space. Iriki et al (1996) showed that through the use of tools by monkeys peri-personal space was concluded to expand to include the tool. However Holmes (2012) has suggested that it may not be an expansion of the space around the hand, but may be the creation of a new area of peri-personal space, or the transfer of an area to an active effector from the real hand location. Whatever the cause, much research has suggested an alteration in the boundaries of peri-personal space as a result of tool use (Farnè & Làdavas, 2000; Holmes et al., 2004; Serino et al., 2007). Therefore in the present study we hoped to further evaluate whether a change in the NHE occurs as the hands separate which could highlight whether peri-personal space expands to compensate for the incongruence, or whether two zones are created when a particular distance is reached.

It has been suggested that the model presented by Makin et al. (2008), which argues that vision of a fake limb and proprioceptive input from the real limb are integrated (with weight given to the visual input when the hand is static), may be altered if the hand is moving. Particularly that if the visual hands movements were similar (or identical) to the proprioceptive hand then peri-personal space might be recalibrated, as in the RHI, so that the real hand is ignored while the visual hand is accepted (Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010). If this is true then the current experiment, in which the participant views a visual hand displaced from their own yet responding to movements, should see

the visual hand maintaining a NHE, while the proprioceptive hand should see a decline in near target facilitation. This is assuming that the NHE is related to items accepted in to the body image. The observation of a NHE using a fake rubber hand, as observed by Reed et al (2006), would suggest that an object incorporated into the body image is effective at producing the result. If an NHE is observed for both hand modalities upon full separation then it could be argued that body image influences the NHE, rather than body schema. If body schema is important then only one hand modality should show an effect due to evidence from Newport et al (2010) suggesting body schema can only incorporate one hand at a time. Alternatively, multiple schema may exist but was not possible to demonstrate in previous research by Newport et al. (2010). Therefore it may be that if an NHE is observed for both hands this could still implicate the body schema.

In summary there are several theories that have tried to explain the existence of a NHE including bimodal neurons and the magnocellular pathway account. Both of these offer predictions as to what the results of this experiment might be. The involvement of bimodal neurons would imply a more reliable NHE when both inputs are closest together and a deterioration of this for both inputs separately. On the other hand the m-cell account would also expect a near target facilitation but due to the biasing of the action-oriented magnocellular pathway. However the m-cell theory would also suggest the possibility of a change in reaction times to far targets as the hands separate due to differences in spatial acuity for cells that process near items compared to those responsible for far.

The additional factor of the participant continuously adjusting and moving the hand could impact upon how the two inputs are integrated. Seeing the movement of the visual hand could cause the body schema to remain with the visual hand, but proprioceptive feedback from the moving unseen hand could also increase awareness of the actual hand position. For example it has been shown that when visual information is degraded a switch to a reliance on proprioceptive information can occur (Bellan et al., 2015), arguably incongruent visual input could be

considered as degraded. Both theories along with other literature would suggest the visual input may be dominant, however this was not observed in the pilot study discussed in chapter 2. The covert nature of the visual and proprioceptive inputs of the hand separating should allow a more detailed evaluation of how the NHE is created and answer questions relating to the importance of body schema.

Based on these theories it was hypothesised that a spatial separation would cause a change in the NHE due to both the representation of the hands in terms of body image or schema, and the visual and proprioceptive inputs becoming incongruent. If the separation is sufficient in disrupting a coherent representation of the hand then the facilitation for near targets may disappear. Alternatively, any disruption may elicit a compensatory mechanism in which the peri-personal space around the hands may expand to try and account for the sensory discrepancy. This could be reflected by decreases in reaction times to far targets as they appear closer relatively within the expanded space.



## Methods

### Design

The experiment employed a 2 x 2 x 5 repeated measures design. The independent variables consisted of target distance (2 levels; near (~2cm) vs. far (~15cm)), hand modality (2 levels; vision vs proprioception) and separation amount (block), which was divided into 2cm blocks, (5 levels; 0-2cm, 2-4cm, 4-6cm, 6-8cm & 8-10cm). The dependent variable was reaction time to targets, measured using a foot pedal.

### Participants

Participants were recruited through the use of posters and also through the University of Nottingham's online recruitment system, SONA. Participants recruited were between the ages of 20 and 28 ( $M = 23.17$ ,  $SD = 2.32$ ), the majority being undergraduate and postgraduate students. All gave informed consent and were aware that they had the right to withdraw at any time.

Power calculations were performed prior to the experiment. These suggested that if 24 participants were recruited this would result in a power of .82 to detect a medium effect (Cohen's  $f = 0.25$ ,  $\alpha = 0.05$ ), or a power of .99 for a large effect size ( $f = 0.40$ ).

### Stimuli

As in the pilot, targets were small red circles that appeared either near (~2cm) or far (~15cm) from the tip of the middle finger. Targets appeared in 4 possible locations, similar to the displaced condition in the pilot experiment. However, as the hands were gradually being separated for the present experiment, the targets moved at the same rate, meaning they were always in line with the middle fingers on both the visual and real hands. The green fixation cross was also tied into the adaptation and moved centrally to remain between all possible target locations (see Figure 3-2). The adaptation, which creates the illusion that the hand is not moving constantly, works by causing the participant to shift their hand slowly rightward in order to keep it between the bars, however the visual image displayed is shifting leftward at the same rate meaning it appears

as if the hand remains in the same location. Instead it appears as if they are making tiny adjustments to keep within the bars.

A questionnaire was administered to the participants verbally from the experimenter. This comprised of 13 questions; 3 measuring ownership; 3 measuring agency; 2 measuring presence; 3 measuring size or shape changes; and 2 measuring sensations (see Table 1 for full of questions). Participants were asked to respond using a likert scale that ranged from +3 for strongly agree, to -3 for strongly disagree. 0 was a valid answer and represented neither agree nor disagree.

Table 1: Questionnaire administered verbally to participants regarding how they felt about their hand after viewing it in MIRAGE.

<b>Question Type</b>	<b>Question</b>
<b>Ownership</b>	The hand I saw felt like it was part of my body.
<b>Ownership</b>	The hand I saw belonged to me.
<b>Ownership</b>	It felt as if I had more than one right hand.
<b>Agency</b>	It felt like I was in control of the hand I was looking at.
<b>Agency</b>	It felt like my hand was out of my control.
<b>Agency</b>	It seemed as if the virtual hand had a will of its own.
<b>Presence</b>	It feels like I am looking directly at my hand, rather than at a video image
<b>Presence</b>	I was controlling the hand I saw
<b>Size/Shape</b>	My hand felt heavier than usual
<b>Size/Shape</b>	My hand felt lighter than usual
<b>Size/Shape</b>	My hand felt bigger than usual
<b>Sensations</b>	I felt unusual sensations in my hand, such as tingling, itching numbness and/or burning.

## **Procedure**

Participants placed their right hand within the MIRAGE and viewed it via the mirror (see Pilot, chapter 2, for details on the MIRAGE). They were required to hover their hand above the work surface so they would not receive any tactile information and primarily relied on the visual and proprioceptive information.

As they held their hand hovering, they were asked to keep it within the black bars which were gradually encroaching upon the hand. This was demonstrated to the participant at the start by the experimenter who moved their hand to where the bars were and showed them that their hand was no longer visible as the bars were covering the hand. They were informed that they may need to make slight adjustments to the positioning of their hand to ensure that it was always in the centre of the visible space. Participants were unaware that this was actually the adaptation stage in which they saw their hand remain in the same location but were in fact moving their hand gradually rightward, separating the seen and felt hand locations. They received a practise go at this to ensure they understood the procedure and to familiarise them with the process. Figure 3-1 illustrates the encroaching bars which have been changed to blue for pictorial clarity. During the experiment the black bars were detectable due to the contrast of the MIRAGE background being slightly lighter.



Figure 3-1: Left image shows pre adaptation hand. Right: bars have encroached fully, real hand has moved 10cm to the right post adaptation.

Figure 3-1 shows the hand positions pre- and post-adaptation. The location of the real hand was not visible to the participant due to the bib which extended from the MIRAGE and was secured around the neck of the participant, covering their arm.

Whilst completing this adaption, the targets would appear in the 4 possible locations pseudo-randomly, 10 in each distance block. Participants had to respond as quickly as possible every time they saw a target, via foot-pedal response. The adaptation was set to the slowest increment of 2 pixels per second which resulted in it taking 79 seconds to complete one adaptation. This also meant that the encroaching bars were very slow allowing participant's time to attend to targets and ensure their hand was always visible. Target appearance and duration was the same as described in the pilot.

The adaptation was repeated 8 times per participant, resulting in 320 targets. Between each adaptation participants removed their hands from the MIRAGE and had a brief break before replacing their hand back

within MIRAGE. This was to ensure they did not realise their hand had moved by having to shift it to start each adaptation again. The questionnaire was verbally administered by the experimenter at the end of the session.

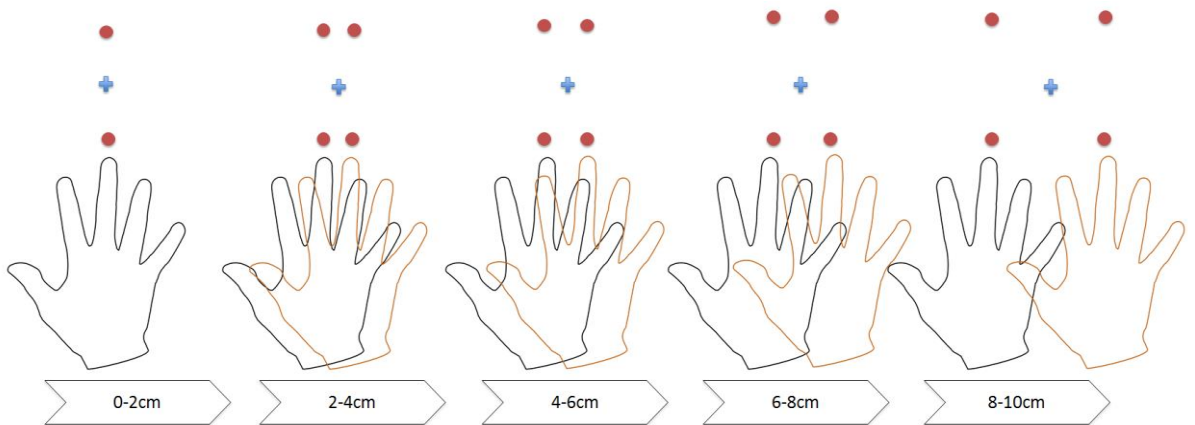


Figure 3-2: Procedural diagram representing target locations as the hands separated during the adaptation. Black is the visual hand, orange unseen real hand.

## Results

The raw data were processed using LabVIEW to divide reaction times in to the distance blocks. Reaction times were separated in to near and far for distances 0-2, 2-4, 4-6, 6-8 and 8-10cm. The visual hand targets were coded as non-moving. This resulted in 32 trials for each participant for both the visual and proprioceptive hands at each block of separation. These reaction times (RT) were then averaged to give one RT for near and one for far for each hand and each block per participant.

### Reaction Time Data

Hand modality (visual and proprioceptive), target distance (near and far) and block (1=0-2cm, 2=2-4cm, 3=4-6cm, 4=6-8cm, and 5=8-10cm) were input as I.V.'s for the first repeated measures ANOVA. The results showed a significant main effect of hand modality,  $F(1,23) = 4.72$ ,  $p = .04$ ,  $\eta_p^2 = .17$ , with the means in milliseconds demonstrating that on average visual hand targets ( $M=446.80$ ,  $SE=12.37$ ) were responded to faster than proprioceptive hand targets ( $M=451.13$ ,  $SE=12.57$ ). A main effect of target distance was also shown,  $F(1,23) = 22.89$ ,  $p < .001$ ,  $\eta_p^2 = .50$ , demonstrating that near targets ( $M=442.33$ ,  $SE=12.14$ ) were responded to faster than far targets ( $M=455.59$ ,  $SE=12.86$ ) confirming the presence of a NHE. Furthermore a significant main effect of block was also shown,  $F(4,92) = 3.17$ ,  $p = .01$ ,  $\eta_p^2 = .12$  with simple contrasts highlighting differences between block 1 and 3,  $F(1,23) = 6.57$ ,  $p = .01$ ,  $\eta_p^2 = .22$ .

A significant interaction was found for hand modality and block,  $F(4,92) = 3.20$ ,  $p = .01$ ,  $\eta_p^2 = .12$ , suggesting that collapsed across target distance reaction times for each block varied depending on the hand modality. Figure 3-3 shows for blocks 1, 2 and 3, reaction times for both hand modalities are similar, but at blocks 4 and 5 the difference between the hands increases. Contrasts comparing each block to block 1 showed a significant interaction between blocks 1 and 4,  $F(1,23) = 6.94$ ,  $p = .015$ ,  $\eta_p^2 = .23$ . Figure 3-3 suggests that it was the proprioceptive hand that saw

increased reaction times whereas the visual hand remained more stable across blocks.

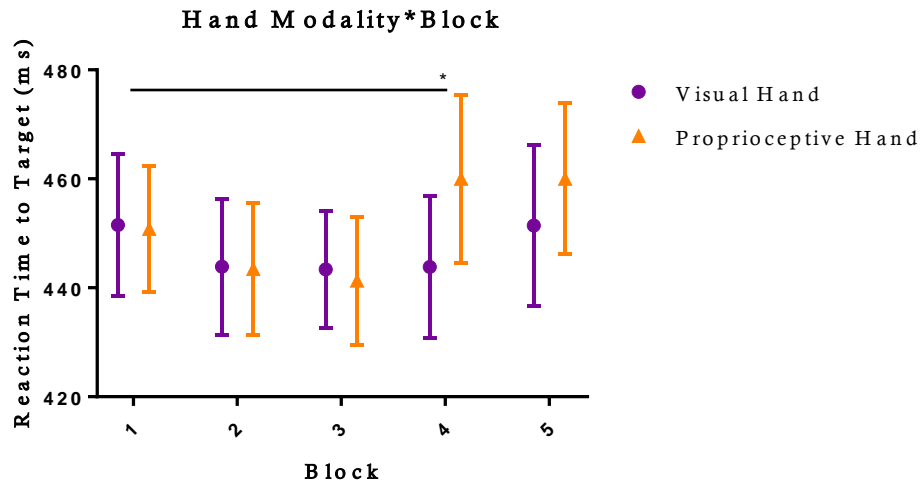


Figure 3-3: Interaction between hand modality and block. Block 4 (6-8cm) significantly different to block 1 (0-2cm). Proprioceptive hand was slower than visual hand at this point.

No significant interaction was discovered for hand modality and target distance suggesting that regardless of separation amount the difference between near and far targets did not significantly differ between the two hand modalities.  $F(1,23) = 1.38, p = .25, \eta_p^2 = .06$ .

A second interaction was found to be significant however, between target distance and block,  $F(4,92) = 2.81, p = .03, \eta_p^2 = .11$ . The interaction shows, with hand modality collapsed, the difference between near and far targets changed depending on the block. Contrasts showed a significant quadratic contrast  $F(1,23) = 6.887, p = .015$ , indicating that the difference between near and far targets gradually decreased and was at its lowest at block 3, before gradually increasing again, as can be seen in Figure 3-5. The graph shows the change to be coming from far targets in which they are responded to faster, diminishing any difference between near and far targets. Figure 3-4 shows the reduction in the NHE.

## Near Hand Effect across Blocks

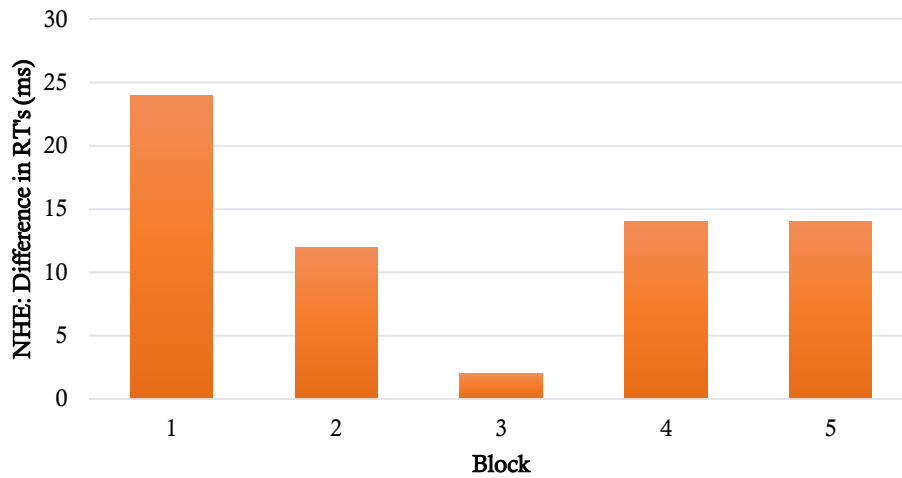


Figure 3-4: Graph to illustrate the changes in the NHE for the Target Distance and Block interaction. As shown here, by block 3 the NHE is nullified but returns for blocks 4 and 5.

The three way interaction between hand modality, target distance, and block resulted in a non-significant outcome,  $F(4,92) = 1.45$ ,  $p = .23$ ,  $\eta_p^2 = .06$ , meaning RTs between near and far targets were not significantly different depending on hand modality and separation amount.

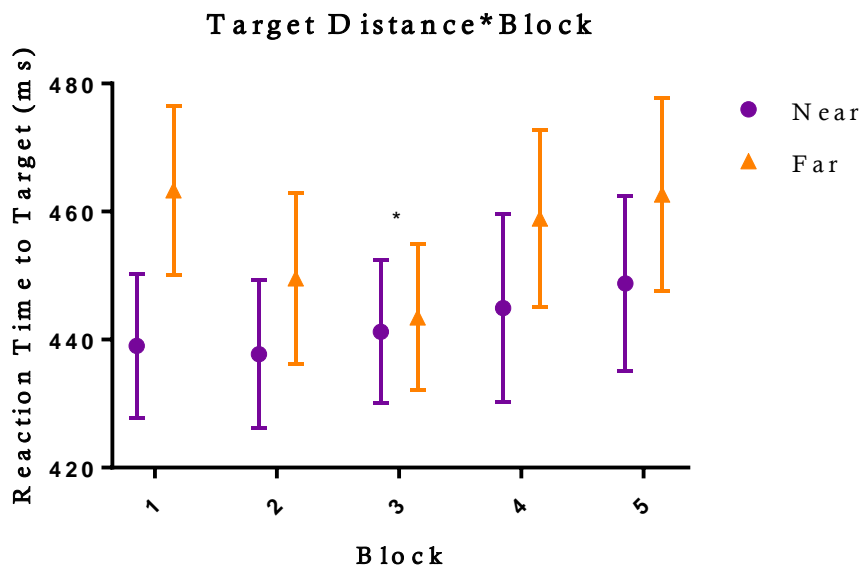


Figure 3-5: Interaction between target distance and the amount of separation of the hands. Contrasts showed difference between near and far was significantly smaller at block 3 compared



To further investigate the target distance\*block interaction a further two ANOVAs were performed, one for each target distance. For near targets the results of a repeated measures ANOVA showed no significant main effects for hand modality,  $F(1,23) = .32, p = .58, \eta_p^2 = .01$ , and block, nor a significant interaction,  $F(4,92) = .94, p = .45, \eta_p^2 = .04$ . This suggests that the changes observed in the interaction are not due to changes in reaction times to the near targets.

The results of the repeated measures ANOVA for far targets showed a significant main effect of hand modality,  $F(1,23) = 4.28, p = .05, \eta_p^2 = .16$ , and block,  $F(4,92) = 3.94, p = .005, \eta_p^2 = .15$ . The interaction was also significant,  $F(4,92) = 3.18, p = .017, \eta_p^2 = .12$  with contrasts highlighting block 4 being significantly different to block 1,  $F(1,23) = 4.87, p = .038, \eta_p^2 = .18$ . These results show that it was a change in reaction times to far targets that influenced the results of the main ANOVA.

### **Questionnaire Data**

Questionnaire data in which participants gave a verbal rating using the scale -3 (strongly disagree) to +3 (strongly agree) to rate their perceptions of the virtual hand was collected for every participant. This included control questions which should have been inversely scored for analysis e.g. responding +3 for 'my hand felt lighter than usual' should have meant that -3 was scored for 'my hand felt heavier than usual'. During analysis the control questions were inversed to give one relatable score for each category of question. All questions within each category were then collapsed to give an overall score, for example 'The hand I saw felt like part of my body', 'It felt as if the hand I saw belong to me', and 'It seemed as if I had more than one right hand' (score inversed), were all collapsed together to give an overall rating of perceived ownership.

Figure 3-6 summarises the results. Positive scores for Ownership, Agency, and Presence, indicate that participants almost all strongly agreed that the hand they saw felt like their hand. Negative scores for Sensations and

Size/shape indicate that the virtual hand did not elicit unusual sensations or perceived changes in the size or shape of their hand.

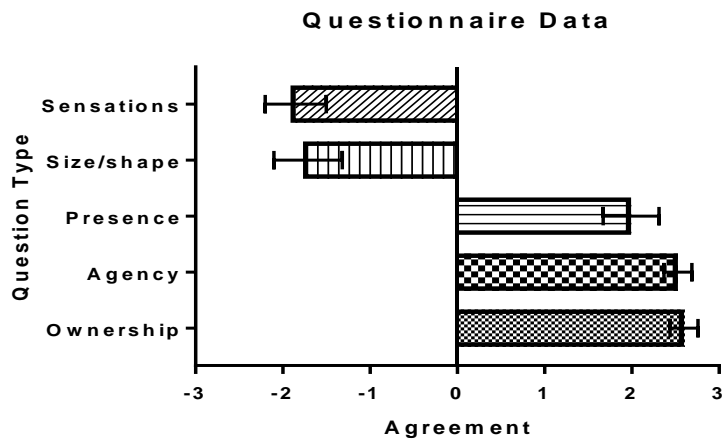


Figure 3-6: Graph showing ratings of the virtual hand on different measures including ownership, agency, and presence which scored highly. The hand was also rated on changes in size or shape and unusual sensations.

## Discussion

The reaction time data shows an important interaction between target distance and block suggesting that regardless of hand modality, the reaction times to near and far targets differs depending on the amount of separation. Planned comparisons comparing each block to the first, in which the hands are only 1cm apart on average, shows block 3 to be the point at which the difference between near and far targets is significantly altered meaning that a distance of 4-6cm is critical. Means show that reaction times to far targets change significantly across blocks, rather than a change to near targets. This result was partly unexpected as a change to the near facilitation was hypothesised.

However a change to far targets was a possibility if the m-cell account was correct. It is possible that targets near the hand are enhanced by the magnocellular pathway which has low spatial acuity compared to p-cells which likely process stimuli in far hand space. A spatial separation could have had more of an effect on the far targets due to a higher spatial acuity. Therefore the separation may have allowed far targets to be processed relatively faster than before due to the recognised change in location. This change may have been perceived as motion of the stimuli and was therefore detected faster than stimuli appearing stationary. Furthermore stimuli shown to move (usually towards the body) have produced stronger neuron activation than when they are still (Graziaon & Gross, 1993).

Secondly, due to the task demands, attending to multiple target locations (even though they appeared iteratively) could have altered which visual pathway to bias. As illustrated by Goodhew and Clarke (2016), when multiple items are presented such as a visual search task, p-cells appear to be prioritised to allow detailed evaluation of multiple items at the cost of faster detection of a single item. If the number of possible target locations did cause a prioritisation of p-cells over m-cells then this could mean that all targets were processed in a similar way and nullify the influence of the hand. This could explain the reduction in RTs for far targets as they are

treated in a similar way to near targets. However this does not explain why after 4-6cm RTs increased again.

As previously illustrated visual and proprioceptive inputs separately do not create as reliable a NHE as they do together (Reed et al. 2006). The bimodal neuron theory would suggest this is because the neurons have a stronger response to visual stimuli that are in peri-personal space due to the expansion of receptive fields around the hand. These receptive fields have been shown to shift towards a visual hand, but not all neurons respond this way, others have a stronger response when the unseen real hand is moved (Graziano, 1999). Therefore it could be argued that a NHE is less reliable when the inputs are separated due to not recruiting as many bimodal neurons. The results here do suggest that the amount of separation changed reaction times as shown by the main effect of block. Also the significant interaction for target distance and block would also suggest that separation between the two inputs did affect reaction times. This fits with previous research and suggests that visual and proprioceptive information is critical to the reliability of the NHE.

The lack of a significant interaction between hand modality and target distance suggests that visual input was not dominant as speculated in the introduction. This contradicts part of the m-cell account that implies that vision of the hand is responsible for the biasing of the magnocellular pathway and it was therefore expected that vision may be dominant. If the visual hand had received enhanced m-cell processing and the proprioceptive hand had not then the difference between near and far targets for the real hand would be smaller than that of the visual hand.

However there was a significant main effect of hand modality showing that visual targets overall were responded to faster than proprioceptive hand targets. These results suggest that the difference between near and far (the NHE) did not differ depending on the hand modality, however when combining near and far targets across all blocks the reaction times for the visual hand were faster. Therefore it could be argued that this provides evidence to support the m-cell account as it was expected that

the visual hand would provide faster reaction times overall due to visual input being responsible for the biasing of the m-pathway. The lack of interaction could be the result of the trade-off between near and far targets which would occur if the m-cell account is correct. For example, if the visual hand is being recognised as the only hand and a facilitation is occurring for the near targets this would also mean that the far visual hand targets have a slower reaction time due to the cost of promoting the m-cells over the p-cells. However if no facilitation of near hand targets occurs (to the proprioceptive hand) then the near and far targets would likely have the same reaction times as each other meaning that the means for both hands, regardless of target distance, would be equal.

A consideration highlighted in the introduction section of this chapter was the presence of two active hands and what effect this might have on the body schema. Newport et al. (2010) suggested that the body image is capable of adding illusory limbs, but the body schema has been shown to only hold the representations of one hand. In the present experiment both the visual and the unseen proprioceptive hands are active as they need to adjust for the encroaching bars. Often the visual input will be considered dominant, and therefore logic dictates the visual hand will be accepted in to the body schema, this was illustrated in the study by Newport which showed that participants accepted the visual temporally synchronous hand in to both the body image and schema as measured by the direction of their reaching movements to a target. However in the present experiment due to the proprioceptive hand not remaining static participants may have had a greater awareness of their unseen hand location (Paillard & Brouchon, 1968).

The absence of a three-way interaction suggests that hand modality did not affect the difference between reaction times to near and far targets as the hands separated. However when collapsing across target distances the other significant interaction showed that proprioceptive hand targets were on average slower at 6-8cm of separation than the visual hand compared to when the hands were together. This perhaps indicates that the visual hand is being stored by the body schema hence seeing a stronger

facilitation effect, over the proprioceptive hand. However, the proprioceptive hand still created a facilitation for the near target, therefore raising the question of what factors are required to influence the processing of near hand space? Due to the increased facilitation for the visual hand it could be argued that the body schema plays a role, however some other processes must also be effective.

The pattern of the data, particularly the target distance\*block interaction term, shows that far targets received faster reaction times as the hand separated, peaking at 4-6cm and then gradually increased again. There are several possible explanations for this. First, if near hand targets are facilitated by the use of m-cells, which are enhanced in near hand space, then the hands separating would potentially have less of an influence on near targets than far due to m-cells having lower spatial acuity. However an increase as large as 10cm, which is the maximum distance the hands separate in the present study, would surely still be noticeable. Alternatively the spatial separation of the hands could result in a reduction in the effectiveness of the magnocellular pathway to bias near targets and in turn reduce the cost that was imposed on the processing of far targets. However this would mean that near targets would have seen an increase in RTs as well as a decrease for far.

Second, as the hands separate the representation of the hand may be less stable due to the incongruent sensory information. It has been suggested that the PPC is responsible for trying to compensate for this uncertainty (Clower et al., 1996) which could result in an expansion of peri-personal space around both hands or the remapping of space (Bolognini & Maravita, 2007). As a result, the far targets are now relatively closer within the peri-personal space than before which could explain their facilitation. The near target RTs may already have been at optimal due to them being less than 2cm from the fingertip which may explain why no changes to the near target were observed.

A third option is that a new hand representation was created somewhere between the two inputs, likely 60% towards the visual hand as previously

illustrated (Ratcliffe & Newport, 2016), which could also have an expanded peri-personal space. Alternatively a new representation could have shifted the visual receptive fields on the bimodal neurons meaning that targets appearing in line with the visual hand would have been perceived as closer than those in line with the proprioceptive hand. This could explain why overall visual hand targets were responded to faster.

The results of the questionnaire could suggest that participants were either not aware of the covert separation of their visual and real hand due to high ratings of ownership, agency, or presence, or a small 10cm separation was not enough to impair these perceptions. However, since it was not directly asked of participants whether they were aware that their hand was moving it is possible that they did have awareness but still took ownership over both limbs. Therefore it can be concluded that the separation of 10cm did not disrupt feelings of ownership, agency, and presence, nor did it create unusual feelings in the hand or change perceptions in regard to size and weight.

Despite evidence presented by Iriki (1996) suggesting that peri-personal space can be extended through tool use, Holmes (2012) offered a review of the findings and argued that the results presented could be the consequence of numerous hypotheses, potentially invalidating their conclusions. It was noted that many researchers study the potential extension of peri-personal space by placing visual stimuli at the tip of the tool and measure the strength of response to both visual and tactile stimuli, based on the principle that there should be a stronger response together if recruiting bimodal visual tactile neurons that process peri-personal space. However presenting stimuli that appear along the tool and close to the hand is often overlooked in favour of just testing stimuli at the tool's tip. By doing this it is unclear whether the peri-personal space has expanded to encompass the entire tool, hand, and the very tip of the tool, or whether two zones have been created (ignoring the middle of the tool), or whether the tip of the tool is now the only area recruiting the use of bimodal neurons.

Iriki (1996) claimed to show an extension of peri-personal space encompassing the tool, however the eye position of the monkey was not controlled for, nor were measurements for the visual receptive field size reported. Holmes (2012) argued that these oversights call the entire validity of the study in to question. The results of the present study could suggest an answer to the question of what is happening to the peri-personal space. The results could be interpreted as showing an initial expansion of peri-personal space, with far targets being included due to the relative change in size, hence the reduction in the difference between near and far targets. The formation of two zones could then be illustrated by an increase in the difference between near and far for blocks 4 and 5. Therefore these results could suggest that a distance of approximately 4-6cm is the maximum amount the peri-personal space can expand before collapsing to create two distinct zones from 6-8cm.

Previous research investigating distances between the real hand and a rubber hand in the RHI have presented conflicting evidence over the maximum distance allowed between the hands for the illusion to still work. Some research has suggested anything over 27.5cm causes a significant reduction in the strength of the illusion (Lloyd, 2007), while others have suggested that distance between the hands does not reduce the illusion (Zopf, Savage, & Williams, 2010). The authors suggested that these differences in results were due to crossing the midline. However these examples may actually be referring to the distances between two distinct zones of peri-personal space, rather than the extension of space. With the results of this study in combination with past research it might be hypothesised that a RHI in which the hand is presented as overlapping (positioned above the real hand to allow the overlap in lateral distance) might be encompassed within the peri-personal space, whereas a hand positioned next to the real hand may create a new zone of space as suggested in the present results. Testing this difference however could be problematic. An identification type paradigm (Adam, Bovend'Eerd, van Dooren, Fischer, & Pratt, 2012) could be used with letters presented in near and far positions to the real hand position, the rubber hand whilst



overlapping the real hand (<6cm separated), and at a further separation. If there is an expansion of space around the middle distance hand then the far letters may have superior identification rates compared to those in the other two conditions due to the relative distance of 'far' if the zone is expanded.

In summary the results of the present study would suggest a combination of theories. The significant interaction of target distance and block suggest that both visual and proprioceptive inputs together produce a more reliable NHE than when they are separated. This supports the inclusion of bimodal neurons and the shifting of receptive fields. However these results could also offer support to the m-cell account due to a change in far target reaction times rather than near. It could be argued that items near the hand are enhanced due to the m-cell pathway preparing the hand to take action but also that the receptive fields of bimodal neurons that move with the hand aid in the detection of near hand targets. The pattern of results presented in this chapter illustrating what happens to the processing of near and far targets as the hands separate would indicate an initial expansion (and hence a reduction in relative difference between near and far) followed by the creation of two distinct areas. Using tDCS to modulate the posterior parietal cortex may alter the point at which these two zones are created by effecting the way the visual and proprioceptive signals are being processed. The following chapter sought to explore this further by examining the role of the PPC in the creation of the NHE through use of anodal, cathodal, and sham tDCS. Modulation to the PPC was expected to alter the way visual and proprioceptive signals were being integrated which may change any adaptation to peri-personal space.

## **Chapter 4 The Effects of tDCS on adapting to a Spatial Separation Between Seen and Felt Hand Locations.**

The results of the previous experiment showed that a spatial separation between the visual and proprioceptive hand inputs changed the way space around the hands was processed as demonstrated by changes in the NHE. In particular, a two-way interaction was shown between target distance and the amount of spatial separation suggesting that the NHE was significantly altered based on the amount of separation, but did not differ between hand modalities. This could suggest that the vRFs around the hands first expanded making the relative distance of the far targets closer, and then possibly separates in to two distinct zones (as seen by the gradual increase between near and far targets for both hand modalities). The other interaction between hand modality and block suggests that overall reaction times changed between the two hands depending on the separation however the critical difference between near and far did not. Overall visual targets were responded to faster. The present experiment aimed to follow up these results by using transcranial direct current stimulation (tDCS) to modulate the effect of a spatial separation on how the hands process the peri-hand space.

tDCS is a safe, non-invasive brain stimulation technique that has been shown to modulate the likelihood of the occurrence of action potentials of the targeted region. A weak electrical current is applied to the scalp through small sponge encased rubber electrodes, one placed above the brain region of interest while the other acts as the reference electrode completing the circuit (Nitsche & Paulus, 2000). tDCS is thought to have polarity specific effects (Antal et al., 2003; Nitsche & Paulus, 2000; Priori, Berardelli, Rona, Accornero, & Manfredi, 1998), however the reliability of this is currently debated (Dyke, Kim, Jackson, & Jackson, 2016). Anodal stimulation should depolarise the resting membrane potential creating an excitatory effect, while cathodal hyperpolarises the neuron creating an inhibitory effect. Application of tDCS has been shown to

create temporary changes in cortical excitability that can last after the duration of the stimulation. These after effects depend on the length of stimulation (Nitsche & Paulus, 2001), but therefore allow tDCS to be applied between testing sessions to then permit a comparison between pre and post tasks. This comparison should highlight the direct effect of tDCS on the task. In the present study a pre/post design was employed in which participants completed the same task before and after stimulation. (Further details pertaining to tDCS are covered in the methods section of this chapter).

So how might applying tDCS prolong a NHE as visual and proprioceptive information becomes incongruent? The posterior parietal cortex (PPC) is known to be responsible for the processing of multisensory integration, specifically relating to the body and remapping of peri-personal space (Bolognini & Maravita, 2007; Giummarra et al., 2008; Graziano & Botvinick, 2002; Lloyd, 2007). But critically activation in the PPC has suggested it plays a role in compensating for incongruent multisensory information (Hagura et al., 2007). With this in mind, altering the excitability of this area could interfere with or potentially improve how the visual and proprioceptive inputs are being integrated during our spatial separation adaptation.

Furthermore, the parietal cortex has also been implicated in the processing of stimuli in peri-personal space. For example, selective BOLD responses to stimuli presented up to 100cm from the hand, but not further (Claudio Brozzoli, Gentile, Petkova, & Ehrsson, 2011). It has also been argued that the parietal cortex plays a central role in mediating the NHE not only because of its function of sensory integration but also due to its involvement in action planning, and spatial attention (Tseng, Bridgeman, & Juan, 2012). Moreover, TMS to the PPC has been shown to disrupt visual search (Ashbridge, Walsh, & Cowey, 1997; Ellison, Rushworth, & Walsh, 2003; Lane, Ball, Smith, Schenk, & Ellison, 2013), effect line bisection tasks (Ellison, Schindler, Pattison, & Milner, 2004), specifically in near hand space (Bjoertomt, Cowey, & Walsh, 2002), and interfere with movement corrections to targets (Desmurget et al., 1999; Johnson &

Haggard, 2005). These studies highlight the importance of the PPC in tasks requiring interaction with peri-personal space and its necessity in updating sensorimotor representations (Rushworth & Taylor, 2006). Therefore modulation of this region could affect performance on our spatial separation task.

In addition stimuli within extended peri-personal space after tool use has also resulted in activation in the parietal cortex (Brown, Doole, & Malfait, 2011). This extension of space is suggested to be the result of increased vRFs of bimodal neurons which have been shown to reside in the parietal cortex (Iriki et al., 1996). Therefore with the parietal lobe implicated in not only sensorimotor integration but also for the expansion of peri-personal space, targeting this region using tDCS could alter the pattern of results seen in chapter 3.

It was hypothesised that anodal tDCS, which increases excitability, could result in two zones of peri-personal space being created sooner. This is because greater excitation could result in a more fine-tuned assessment of the visual and proprioceptive information, meaning it may recognise the incongruence sooner and separate the two zones rather than trying to compensate for the noise at the start. Alternatively, greater excitation in the PPC could increase the range of the vRFs meaning that the difference between near and far targets would be lessened. Cathodal stimulation was hypothesised to have the opposite effect, while sham stimulation should see no change between pre- and post-stimulation sessions. Previous research using tDCS over the PPC demonstrated faster reactions to targets after anodal stimulation suggesting stimulation enhanced spatial orienting (Bolognini et al., 2010). This would suggest that perhaps anodal stimulation would result in faster overall reaction times in the present study. Therefore we would expect cathodal stimulation to cause a decrease in reaction times. However, due to the variable nature of tDCS it was difficult to make accurate predictions, however a change as a result of stimulation was expected.

Along with the main stage of the experiment (which replicates chapter 3), two additional stages were devised to more thoroughly assess the methodology in terms of positioning of the hand as well as the contribution of visual information and what happens when it is suddenly removed.

For this preliminary stage, participants placed their right hand within the MIRAGE and responded to targets appearing in line with the middle finger. For this condition both the visual and proprioceptive inputs were congruent. Participants would respond to targets in line with the congruent hand but also targets displaced 10cm to the right (the position the proprioceptive hand would be in for the main stage). It was hypothesised that only targets in line with the hand should show an NHE while the displaced targets should show a similar result to that of the block condition in chapter 2.

At the end of the spatial separation adaptation participants would continue to respond to targets but the visual hand was removed. It was hypothesised that two things could happen, either we would find a significant effect of modality in that the visual hand targets would lose all facilitation and only remain with the proprioceptive hand, or that there would be no effect of the immediate removal of visual input due to any expansion in peri-personal space remaining for several minutes as observed in tool use studies.

## Methods

### Design

The present experiment had 5 I.V.'s, stimulation polarity (3 levels; anodal, cathodal, or sham), time of stimulation (2 levels; pre and post), hand modality (2 levels; visual or proprioceptive), target distance (2 levels; near or far), and separation amount or 'block' (5 levels; 0-2cm, 2-4cm, 4-6cm, 6-8cm, 8-10cm). The dependent variable was reaction time to targets as measured by foot-pedal response. Questionnaire responses regarding hand perception was also measured before and after stimulation. Additionally estimates of hand location were recorded at the end of each session.

The experiment was broken down in to stages. The first stage the hand remained stationary with visual and proprioceptive inputs congruent. Targets were tested near and far from the hand and also 10cm to the right (see Figure 4-4). The hand was tested both visible and hidden with order counterbalanced. This stage was designed to test whether a NHE existed for the hand targets but not the displaced targets. It was expected that the hand targets would show a significant difference between near and far both when the hand was visible and hidden. This stage will be referred to as TOGDISP indicating hand modalities were together with the addition of displaced targets being presented.

The main stage (stage 2) of the experiment involved the hand moving covertly away from its visual counterpart as in chapter 3. This stage had the 5 I.V.'s mentioned above.

The final stage (stage 3) was performed at the end of each adaptation in which the visual information for the hand would disappear while the participant continued to respond to a further 8-10 targets. This stage will be referred to as HIDSEP indicating the hand was hidden after modalities were separated. This was designed to measure what would happen to the visual hand targets when vision is removed. Critically would it show that any newly created facilitatory zone would disappear upon sudden removal of the visual hand? The targets would be analysed separately to

see if there was a difference in NHE's for the targets appearing in the location of the now hidden visual hand compared to the proprioceptive hand targets.

### **Participants**

Recruitment posters were used as the only method of recruiting participants, displayed in multiple locations around the University of Nottingham. Upon enquiry potential participants were sent exclusion criteria and study information via email. Once returning the tDCS screening questionnaire (appendix 3) participants were then allocated a timeslot if they were eligible. Only right handed individuals were tested (as measured by the Edinburgh Handedness Questionnaire, appendix 1).

The sample consisted of 24 participants, 6 of whom were male, aged 18-25 ( $M= 21$ ,  $SD = 1.68$ ). All participants took part in each of the three stimulation conditions; anodal, cathodal, and sham. Stimulation order was counterbalanced across participants, with each session separated by 1 week.

### **Stimuli**

Target appearance was the same as that described in chapter 3.

A questionnaire was designed to record participants' perceptions of their hand in relation to ownership and unusual sensations. Three questions focused on ownership, including one control for which the score would be inversed for the results. Two questions referred to any unusual sensations such as 'I felt an ache of throbbing in my hand' and one final question asked 'did you feel you hand was moving' to ascertain whether participants were aware of the adaptation process in which the hands were separated. Full questionnaire can be found in appendix 4.

An Adverse Effects questionnaire was given to participants at the start of each session to ensure that they were not already experiencing symptoms that could be worsened by the application of tDCS, such as headache. This was developed based on Brunoni et al., (2011)'s questionnaire. It was

modified to include pseudo measures as control questions (see appendix 5). It was also given to participants at the end of each session.

### tDCS

A Newronika DC-current tDCS machine was used which comprised of the 'HDCstim' (that administered the current through the electrodes connected with wires) and the 'HDCprog' (the programmer for the stimulator). See Figure 4-1.

To ensure stimulation parameters met safety recommendations current density calculations were performed (current strength/electrode size).



Figure 4-1: HDCstim (left) and touch screen HDCprog (right). tDCS machine provided by Newronika.

The target electrode was 5 x 5cm in a sponge holding bag 6 x 7.5cm. Generally, most tDCS protocols chose to stimulate between 1 and 2mA for between 5 and 30 minutes (M. Bikson, Datta, & Elwassif, 2009), with 2mA being the upper safety limit (Iyer et al., 2005). Ideally stimulation intensity should be high enough to induce a change in cortical activity, but also be as low as possible to reduce and prevent any cutaneous sensations for the participant. Therefore 1.4mA was selected as this resulted in a current density of 0.031mA/cm<sup>2</sup> which is within the recommended safety range for active stimulation. (Nitsche et al, 2007).

The reference electrode was 6 x 8.5cm in a sponge holding bag 8.5 x 10cm. Stimulation of 1.4mA resulted in a current density of 0.016mA/cm<sup>2</sup>. This is below the minimum threshold of 0.017mA/cm<sup>2</sup> needed to modulate cortical activity (Nitsche et al, 2007), meaning the region beneath the reference electrode should not be effected by the stimulation, as desired. A higher current of 1.5mAs would have meant the reference electrode



would have been above the threshold and therefore modulated activity in that region. 1.4mAs was chosen as it was the highest current that still resulted in a below threshold modulation for the reference electrode.

The rubber electrodes are placed inside the sponges which are then connected to wires that feed into the stimulator. The electrodes are secured in place using neoprene caps that firmly press the entire sponge cased electrode on to the scalp. This method is advantageous compared to the use of rubber bands as it applies the most contact with the scalp.

The target electrode was placed over the posterior parietal cortex (PPC) which was located using the 10:20 EEG system to find P4. The PPC is then located 1cm above P4 (Gallace, Soravia, Cattaneo, Moseley, & Vallar, 2014). The reference electrode was placed on the contralateral side of the forehead. Stimulation was applied for a duration of ten minutes after the first task, before repeating the same task post-stimulation. Figure 4-2 shows an example of the montage secured with bands so electrodes are visible.



Figure 4-2: Electrode montage placement. In this example secured with bands so the electrodes are visible. For actual testing a cap was used.

When the stimulator is turned on it begins to ramp up the current to reach the desired level. The ramp up time was programmed as being 5% of the overall stimulation time. In this case that equated to 30 seconds. During

this period participants were likely to feel a slight tingling as the current changes, but these cutaneous sensations usually subsided when it reached the specified current level (Nitsche et al., 2008). These sensations are also present in the sham condition as the current ramps up for 15 seconds before ramping back down, thus eliciting the same cutaneous sensations making participants less aware of what condition they were in.

During the ramp up stage the experimenter observed the stimulation protocol on the HDCstim to ensure the stimulation did not fail. If the stimulation failed it could be due to poor contact with the scalp, or inadequate saline on the sponges. Once these checks were made stimulation would be re-initiated successfully. Figure 4-3 is a diagram to show the stimulation protocols.

All participants received all three types of stimulation (anodal, cathodal, and sham) with each session separated by a week to ensure no cumulative effects of the stimulation over consecutive days that could influence results (Alonzo, Brassil, Taylor, Martin, & Loo, 2012; Boggio et al., 2007; Gálvez, Alonzo, Martin, & Loo, 2013). Sham stimulation mimics the sensation of receiving tDCS but does not alter cortical activity as the current is only applied for the initial 30 seconds. Anodal stimulation should have the opposite effect on the cortex to cathodal stimulation, however often studies find a significant change with one polarity but not the other on a given task (Antal et al., 2001) with cathodal stimulation being less reliable (Jacobson et al., 2012).

The present experiment employed an 'offline' protocol meaning the stimulation was not given at the same time participants completed a task. Instead participants remained inactive during the stimulation time and then recompleted the initial task post-stimulation. This method was chosen to allow a pre-post comparison between testing sessions. There are no clear benefits of one method over the other as both are considered to produce the same results in terms of polarity for cognitive tasks (André Russowsky Brunoni & Vanderhasselt, 2014). However an online approach would be beneficial if time was a constraint. Differences

between polarity specific effects, have been observed when additional tasks have been used to fill the stimulation time which can then affect performance on the main task (Horvath, Carter, & Forte, 2014), therefore participants did not complete an additional task during the stimulation period and sat stationary for the duration.

In terms of the underlying cortical changes, online and offline designs do have different effects but this depends on duration of stimulation. For example, research has shown that the duration of stimulation changes the length of after-effects (Nitsche & Paulus, 2001). For example, after effects of up to 30 minutes has been recorded after receiving 9 minutes of stimulation, whereas increasing this to 13 minutes results in 90 minutes of after-effects. The application of stimulation appears to be cumulative but not necessarily linear (Nitsche & Paulus, 2000). Furthermore, after-effects are thought to be the result of synaptic modification while online effects are due to membrane polarisation (Nitsche et al., 2005). However for the purposes of this study an offline method was appropriate as ten

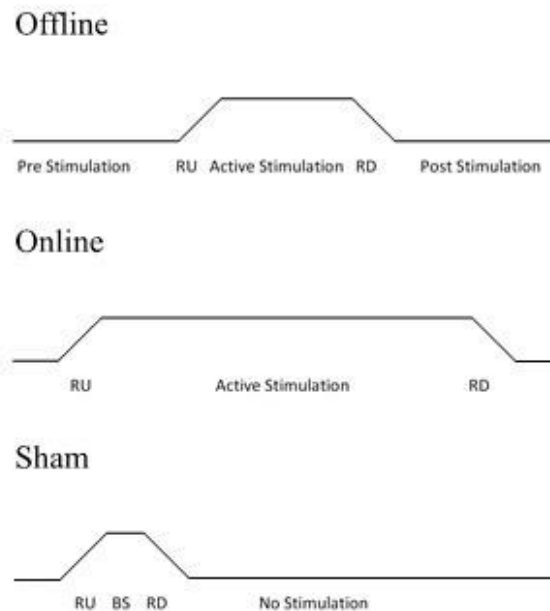


Figure 4-3: Stimulation protocol illustration. Offline and sham used for present study. RU = ramp up, RD = ramp down, BS = brief stimulation.

minutes of stimulation created after-effects that lasted the duration of the task.

Each stimulation session begins with a ramp up of the current (including sham) which may be detected by the participant, however some do not report feeling any sensation under the electrode. After 30 seconds the current reaches its maximum output and remains on for the duration of the protocol before ramping back down at the end.

A repeated measures design was chosen primarily due to research suggesting the variable nature of tDCS in terms of reliability across participants. Individual differences between participants can play a role in the outcome of polarity specific effects for example research has shown differences in current responsiveness (Li, Uehara, & Hanakawa, 2015), gender (Chaieb, Antal, & Paulus, 2008; Lapenta, Fregni, Oberman, & Boggio, 2012), and anatomical differences (Datta, Truong, Minhas, Parra, & Bikson, 2012). Therefore it was decided that having the same participants return for each polarity session was important to keep consistent to avoid these confounding variables. Of course there was likely variation within our sample, but by having the participants return for further sessions reduced the number from 72 to 24.

Exclusion criteria questionnaires were administered upon enquiry during the recruitment stage. Criteria ranged from neurological to scalp conditions. No serious adverse effects have been reported for the use of tDCS within the 1-2mA range (Arul-Anandam, Loo, & Sachdev, 2009), however most studies have used the stricter TMS screening criteria. Mild and temporary side effects that have been consistently observed include redness and tingling under the electrode, as well as headaches (Andre Russowsky Brunoni et al., 2011). Cutaneous sensations can be reduced by applying more saline whilst being careful not to apply too much causing the current to disperse further than the electrode.

### **Procedure**

Having already completed the initial screening forms via email, on arrival participants completed the adverse effects questionnaire that asked them

to rate a list of symptoms to ensure they were well enough to receive tDCS without the risk of worsening these symptoms, for example headaches. (See appendix 5 for Adverse Effects Questionnaire).

As described in the design section the procedure was broke down in to stages. The first stage (TOGDISP) required participants to place their hand in MIRAGE and keep it stationary. They would then simply have to initiate a foot-pedal reaction time response every time a target appeared. Targets appeared one at a time in 4 possible locations, either near or far from the participant's hand, and in line with the middle finger, or in a fixed location 10cms to the right of the other two targets. Both the visual and real hand remained congruent for this stage. A fixation cross was presented centrally between all possible target locations (see Figure 4-4). For half the trials the hand remained visible during target presentation. Hand visibility order was counterbalanced across participants. This stage lasted for just under 3 minutes (2 x 79 seconds) with 96 target presentations (48 x 2, one set with the hand visible, one without).

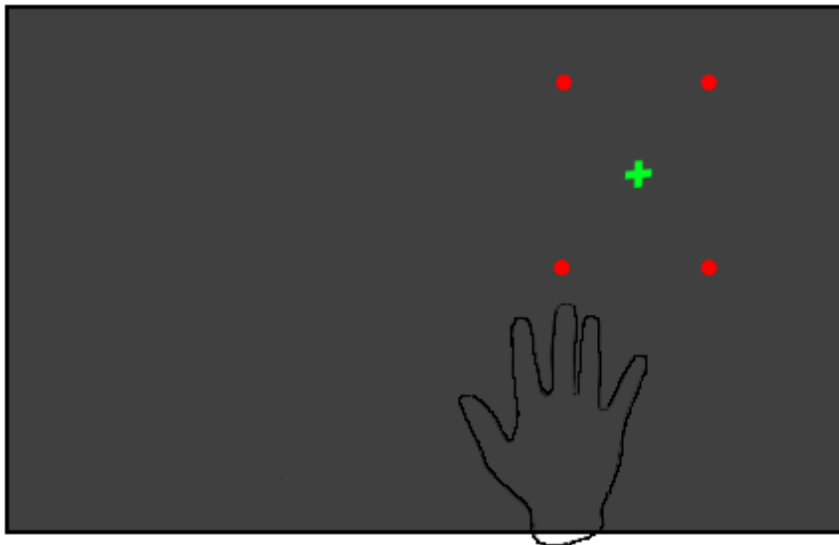


Figure 4-4: Target locations for the stationary hand condition. Two in line with visible (and spatially congruent) hand, two displaced 10cm to the right. Fixation cross presented centrally.

The main stage of the experiment involved participants levitating their right hand within MIRAGE whilst responding to near and far targets presented pseudo randomly. At the same time they also had to keep their hand visible so it was not encroached by the black bars moving slowly towards their hand. This was the adaptation process in which the visual hand was slowly separated from the real hand. This was the same procedure as described in chapter 3, but was completed 6 times. However in addition at the end of each adaptation the hand would become hidden while participants continued to respond to additional targets (appearing in line with both the actual location of their hand, and the last seen visual position) whilst keeping their hand levitating (HIDSEP). An arrow then appeared at the top of the screen starting in the far right corner and gradually began moving leftward. Participants has to say 'Stop' when they believed the arrow was in line with the position of their hand. This was to measure if the stimulation altered the perceived location of their hand. The questionnaire was then verbally administered asking participants to rate how their hand was feeling.

After this initial testing period, participants then received 10 minutes of tDCS, either anodal, cathodal, or sham stimulation. All participants received each type of stimulation after completing all 3 sessions (counterbalanced order). During this stimulation time participants did not engage in any activity and were not permitted to access their phones or other devices. Once stimulation was complete participants then repeated the entire procedure again including the hand questionnaire at the end. The whole procedure lasted 1 hour. Before leaving participants were also required to complete the adverse effects questionnaire to ensure they were not experiencing any effects as a results of the tDCS. If they scored higher than 5 on any measure they were asked to remain with the experimenter until the symptoms subsided, however no participant ever scored a 5 or above.

## Results

### Reaction time Data

The raw data underwent processing in which invalid trials were firstly removed (0 and 2500ms indicated pre-emptive or no response respectively). Trials were then manually inspected on a participant by participant basis with the larger variation being shown as across participants rather than conditions. The method for outlier removal was therefore +/-2SD's based on the means and standard deviations for each participant, collapsed across group.

### *TOGDISP Analysis*

With the removal of outliers only 3.2% of data were removed, well within acceptable limits (Ratcliff, 1993). This section of data analysis refers to the preliminary stage of testing in which participants kept their hands stationary within the MIRAGE and viewed targets appearing in line with their hand (visible and spatially correct) and also targets appearing 10cm to the right in empty space. This was to investigate whether the displaced targets also had a NHE despite no hand information being in line with them. A further condition was run in which the visibility of the hand was removed to test purely the influence of proprioception on targets in line with the hand compared to those aligned with empty space.

### *Sham TOGDISP*

Results of the repeated measures ANOVA for the sham condition showed a main effect of Targetdistance,  $F(1,23) = 9.99$ ,  $p = .004$ ,  $\eta_p^2 = .30$ , but not for Hand ( $F(1,23) = .184$ ,  $p = .67$ ,  $\eta_p^2 = .01$ ), nor was there an interaction for Targetdistance and Hand,  $F(1,23) = .009$ ,  $p = .93$ ,  $\eta_p^2 = .00$ . This suggests that any relative facilitation received by near targets in line with the hand, was not significantly different to those not in line with the hand. This is not what was expected and suggests displaced targets also received a facilitation. Means show that for both target locations (hand and displaced) near targets were responded to faster.

It was also expected that targets in line with the hand would show an NHE even when the hand was hidden, compared to targets appearing displaced by 10cm. This was supported by the absence of a main effect of Visibility. However the Visibility\*Hand interaction ( $F(1,23) = .01, p = .94, \eta_p^2 = .00$ ) and Visibility\*Hand\*Target Distance interaction ( $F(1,23) = .02, p = .90, \eta_p^2 = .00$ ) were not significant which suggests targets displaced 10cm to the right were not responded to differently than those in line with the hand and visibility of the hand did not alter this.

Unexpectedly there was a significant interaction for Timeofstim and Targetdistance suggesting the difference between near and far targets changed post-stimulation,  $F(1,23) = 5.68, p = .03, \eta_p^2 = .20$ . Means show that in the pre-stimulation session near targets were responded to much faster (*near*  $M=429.07$ , *far*  $M=444.57$ ), however post-stimulation this difference narrowed significantly (*near*  $M=426.86$ , *far*  $M=428.70$ ).

#### *Anodal TOGDISP*

The results of the repeated measures ANOVA for the anodal condition showed a significant main effect for Targetdistance,  $F(1,23) = 7.47, p = .01, \eta_p^2 = .25$ , highlighting that overall near targets ( $M=428.88, SE=8.07$ ) were responded to faster than far targets ( $M=435.79, SE=7.30$ ). However there was not a significant interaction between Targetdistance and Hand,  $F(1,23) = 2.06, p = .17, \eta_p^2 = .08$ , suggesting that targets in line with the hand did not receive significantly different RT's to those that were displaced where no hand was present. However, a significant interaction was found for Time\*Hand\*Target Distance indicating that the difference between near and far target RT's was different post-stimulation depending on whether the targets appeared in line with the hand or not,  $F(1,23) = 5.12, p = .03, \eta_p^2 = .18$ .



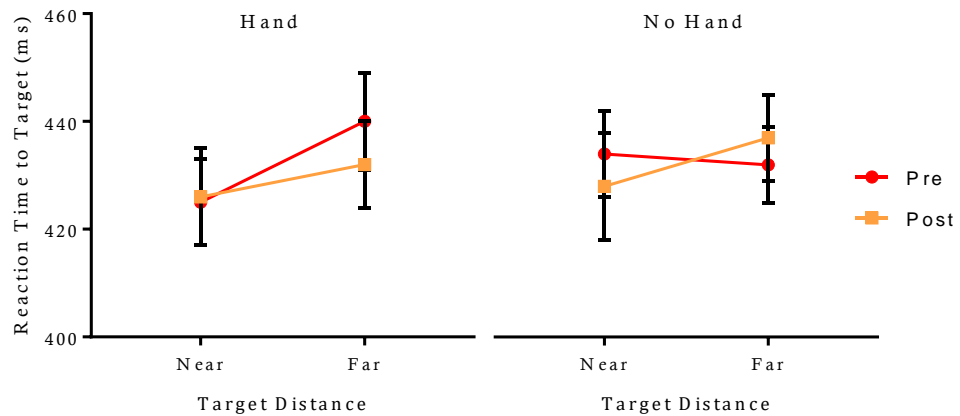


Figure 4-5: Time\*Hand\*Target Distance interaction. Left: targets in line with the participant's hand. Right: targets appeared 10cm to the right receiving no hand input.

As illustrated in Figure 4-5 prior to stimulation targets not in line with the hand did not show an NHE, with far targets being responded to faster than near. However post-stimulation this changed, with near targets seeing a facilitation that was not there before. This differs from the hand condition in which far targets were always detected slower, however after stimulation far targets were responded to slower still. All other main effects and interactions were not significant, including those relating to Visibility of the hand suggesting that visibility of the hand had no effect on RT's.

#### *Cathodal TOGDISP*

The repeated measures ANOVA for cathodal stimulation showed a significant main effect of Targetdistance,  $F(1,23) = 9.12, p = .006, \eta_p^2 = .28$ , along with a significant main effect of Hand,  $F(1,23) = 4.29, p = .05, \eta_p^2 = .16$ . Furthermore a significant four-way interaction was shown for Time\*Visibility\*Hand\*Targetdistance signifying a combined effect of hand visibility, target hand alignment, stimulation, and target distance on reaction times, see Figure 4-6. All other effects and interactions were not significant.

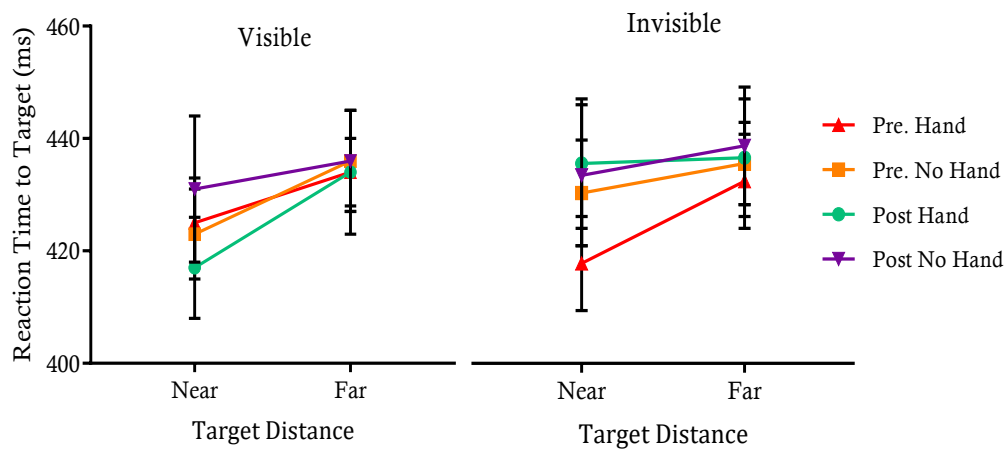


Figure 4-6: Four-way interaction for cathodal stimulation. The difference between near and far RT's is large for targets in line with the hand post-stimulation when the hand was visible, compared to when the hand is not visible.

In summary, all stimulation conditions firstly found a main effect of target distance suggesting near targets overall were responded to faster than far targets. Post sham stimulation the difference between near and far targets appeared to narrow, with far targets being responded to almost as fast as near. However 'post sham' was also post main experiment with the hand adaptation, the influence of this is further discussed in the next section. Anodal stimulation appeared to not show an NHE for the displaced targets pre stimulation, but did post. Cathodal stimulation differed from the other two conditions in that a main effect of hand was found suggesting that targets in line with the hand were responded to differently than those displaced. Furthermore, a 4-way interaction suggests that vision of the hand is critical to the existence of a NHE after receiving cathodal stimulation.

### *Main analysis*

Targets were separated in to 5 distance blocks based on the amount of separation in pixels between the real location and the visual hand information. Averages could then be created for each 2cm block per participant along with the targets that were continually in line with the

real hand. Therefore there were 5 I.V.'s including block (5 levels; 0-, 2-4, 4-6, 6-8 and 8-10cm), hand modality (2 levels; visual and proprioceptive), target distance (2 levels; near and far), polarity of stimulation (3 levels; sham, anodal, and cathodal), and time of stimulation (2 levels; pre and post). The D.V. was reaction time to targets (ms).

To examine the change to the NHE, near RT's were subtracted from far RT's to give one NHE value for each block, modality, time of stimulation, and polarity for each participant. These were then analysed in a repeated measures ANOVA to evaluate if there were differences in the NHE across conditions.

The results of the ANOVA showed no main effects, but did show a significant interaction between Time of stimulation and Block,  $F(4,92) = 4.821$ ,  $p = .001$ ,  $\eta_p^2 = .17$ . All other interactions were not significant.

However contrasts highlighted several significant interactions, including a significant quadratic contrasts for Polarity and Block ( $p=.03$ ). This means show that for both sham and cathodal stimulation the NHE was large for blocks 1 and 2, gradually getting smaller by block 3, and then larger again by block 5, whereas anodal stimulation appeared to have a very small NHE at block 1, with this gradually increasing, see Figure 4-7.

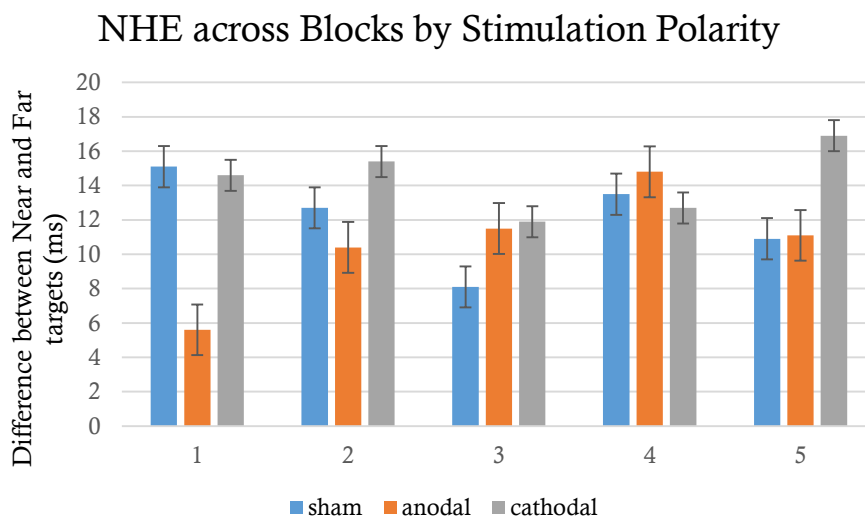


Figure 4-7: Graph illustrating the quadratic contrasts found for Stimulation Polarity by Block.

In relation to the significant interaction, it was shown that there was a highly significant order 4 contrast ( $p < .001$ ). This is illustrated in Figure 4-8. It shows increases and decreases in the NHE at different points depending on whether it was pre or post stimulation.

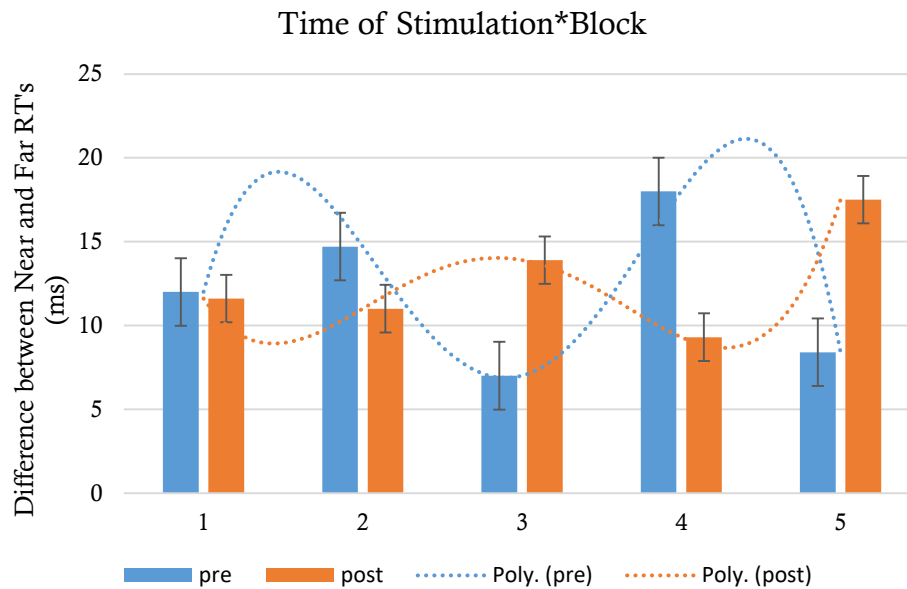


Figure 4-8: Graph illustrating polynomial order 4 significant contrast between time of stimulation (pre vs post) and block (1-5).

In summary these results suggest that the NHE changes as the distance between modalities increases, but that this depends on time of stimulation. No changes between polarities were found suggesting sham, anodal, and cathodal stimulation did not have significantly different effects. These results were not expected as active stimulation should have performed differently to sham. However the change across blocks post stimulation suggests that practise effects of the task may influence RT's as the hand's separate.

For the purposes of addressing the research questions analysis was done for each stimulation condition individually primarily investigating any effect of stimulation by comparing pre and post conditions. Therefore 3 4-way ANOVA's were conducted. Due to the offline method used, a pre/post comparison for each polarity was possible. However it should be

noted that the following analysis does not allow for comparison between stimulation conditions as they were not directly compared.

### *Sham Analysis*

A repeated measures ANOVA was run to compare differences in reaction times to near and far targets before and after stimulation. Of particular interest were main effects of Timeofstim and Targetdistance, along with interactions between Timeofstim\*Targetdistance, Targetdistance\*Block, and Targetdistance\*Modality\*Block. It was expected that sham stimulation would not elicit changes in reaction time, nor would it change the difference between near and far targets over time, however a significant difference between near to hand targets and far was expected. However it was hypothesised that the difference between near and far targets would change as the hands reached different separation amounts (blocks), and that visual information may be dominant. Results showed a violation of sphericity for block ( $X^2(9) = 21.336, p = .011$ ) and the Timeofstim\*Block interaction ( $X^2(9) = 20.70, p = .014$ ). Due to both epsilon values being greater than 0.75 the Huynh-Feldt correction was used for these variables.

In line with our predictions, no main effect of Timeofstim was found,  $F(1,23) = .005, p = .94, \eta_p^2 < .001$ , meaning that overall there was no difference in reaction times between the pre-stimulation session and post-stimulation. A highly significant main effect was found for Targetdistance showing that near targets ( $M=434.13, SE=8.90$ ) were responded to faster than far targets ( $M=446.23, SE=9.13$ ),  $F(1,23) = 43.63, p < .001, \eta_p^2 = .66$ . Similarly, there was no interaction between Timeofstim\*Targetdistance,  $F(1,23) = .62, p = .44, \eta_p^2 = .03$ , as predicted. However, the interaction for Targetdistance\*Block was not significant showing that the difference between near and far targets did not change as the hands separated, when averaging both hand modalities together, despite an overall change in reaction times,  $F(3.44, 79.16) = .62, p = .63, \eta_p^2 = .03$ .

Targetdistance\*Modality\*Block interaction produced a non significant result,  $F(4,92) = 1.68$ ,  $p = .16$ ,  $\eta_p^2 = .07$ ), highlighting that differences between near and far targets were not significantly different depending on hand modality or amount of separation (see Figure 4-9). This is not in line with predictions in which it was hypothesised that the visual hand may generate a different NHE to the real unseen hand as they separated. A summary of these key results, and those for each stimulation condition, can be seen in Table 2.

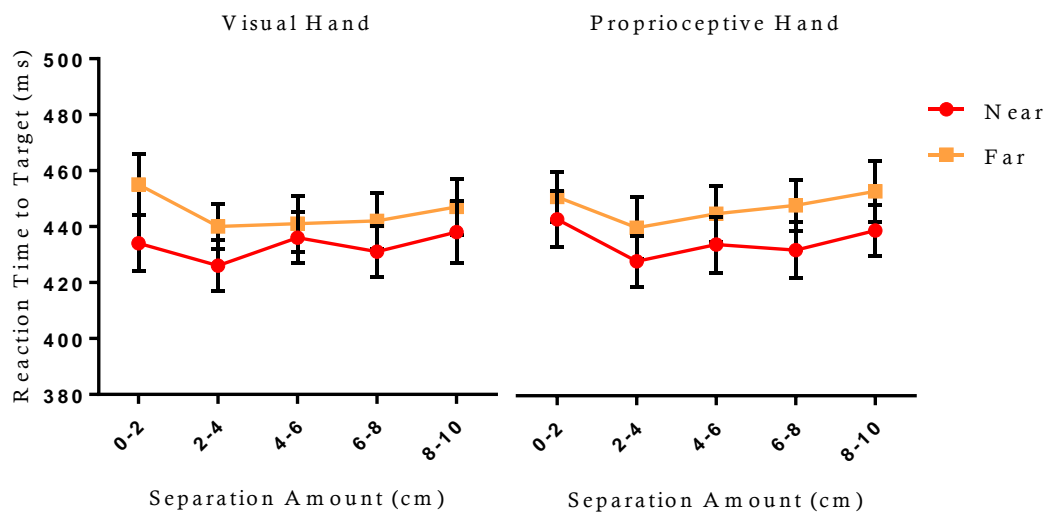


Figure 4-9: Sham condition shows no interaction between Targetdistance\*Modality\*Block meaning hand separation did not change the NHE.

A significant interaction was found for Time\*Modality\*Block,  $F(4,92) = 2.49$ ,  $p = .048$ ,  $\eta_p^2 = .10$ . Although this does not tell us about changes in the difference between near and far targets, it does show changes in overall reaction times as the hands separated. Contrasts reveal significant differences between blocks 1 and 3 (0-2 and 4-6cm),  $F(1,23) = 8.97$ ,  $p = .006$ ,  $\eta_p^2 = .28$ . This could suggest that when the hands are 4-6cm misaligned reaction times to all targets differ post-stimulation depending on hand modality. Means show a decrease in reaction times for 4-6cm separation compared to no separation post-stimulation for the proprioceptive hand (*post block 1*  $M=448.54$ , *block 3*  $M=436.06$ ), whereas for the visual hand there was no change between the blocks after

stimulation (*post block 1 M=446.45, block 3 M=446.88*). Figure 4-10 shows the interaction for blocks 1 and 3 to illustrate the change.

In summary, results of the sham condition show that as predicted near targets are consistently responded to faster than far targets, and there was

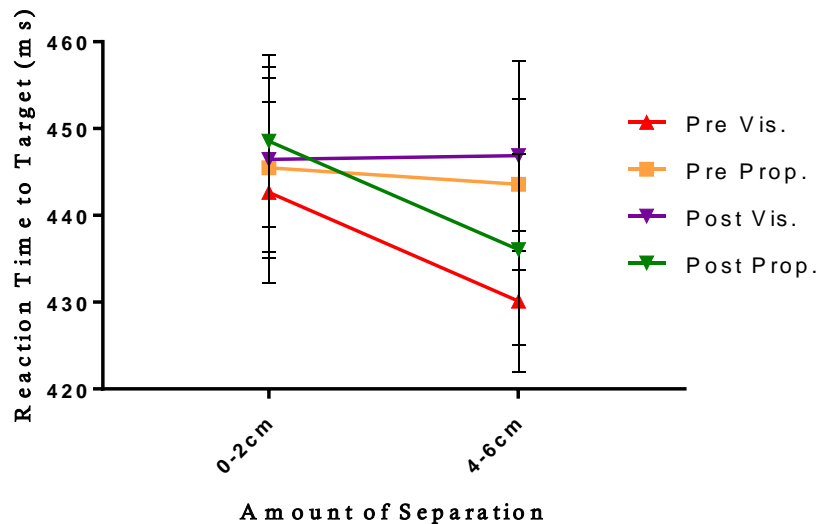


Figure 4-10: Time\*modality\*block interaction comparing block 1 and block 3 as highlighted by contrasts as being significant.

no main effect of time of stimulation. Furthermore, it was predicted that as the hands separated this could change the difference between near and far RT's yet this was not observed. Unexpectedly overall RT's did change post sham stimulation depending on hand modality and amount of separation, however the critical difference between near and far (the NHE) did not.

### *Anodal Analysis*

A repeated measures ANOVA was run for the anodal sessions. If stimulation to the PPC affected the representation of the hand(s) then significant interactions should be observed between time of stimulation and target distance. In line with what has been previously established it was also expected that a main effect of Targetdistance would be found. Additionally, changes between near and far targets across blocks was expected (Targetdistance\*Block), along with possible changes in hand

modality (Targetdistance\*Modality\*Block), and the influence of the stimulation (Targetdistance\*Timeofstim\*Block; Targetdistance\*Modality\*Block\*Timeofstim).

The results showed a violation of sphericity for the Time\*Target distance\*Block interaction term only,  $X^2(9) = 17.01$ ,  $p=.049$ ), and therefore the Huynh-Feldt correction was applied to this term ( $\epsilon=.86$ ).

Results showed a significant main effect of Timeofstim,  $F(1,23) = 5.18$ ,  $p = .032$ ,  $\eta_p^2 = .18$ , and a highly significant main effect of Targetdistance,  $F(1,23) = 28.99$ ,  $p < .001$ ,  $\eta_p^2 = .56$ . Means suggest that overall participants responded faster to targets prior to stimulation (Figure 4-6) and that near targets were responded to faster than far targets ( $M=439.58$ ,  $SE=9.73$ ;  $M=450.29$ ,  $SE=9.72$ ). However the interaction for Timeofstim and Targetdistance did not produce a significant result,  $F(1,23) = .45$ ,  $p = .51$ ,  $\eta_p^2 = .02$ , therefore suggesting that the difference in reaction times to near and far targets did not differ based on the stimulation, near targets were still responded to faster, however the means show both near and far targets had slower reaction times post stimulation (demonstrating the main effect).

However a significant interaction was observed for Timeofstim\*Target Distance\*Block,  $F(3.46, 79.51) = 2.68$ ,  $p = .045$ ,  $\eta_p^2 = .10$ . This would suggest that the difference between near and far targets changes as a result of stimulation depending on the amount of spatial separation between the two hands. Figure 4-11 demonstrates this more clearly showing how the difference between near and far targets is modulated with the pre-stimulation condition presented on the left, post-stimulation on the right. The pattern presented here shows that regardless of hand modality, near targets see a slight facilitation in reaction times at 4-6cm (block 3), with the main difference between pre- and post-stimulation being at block 5 when the hands are completely separated (10cm). Prior to stimulation the difference between near and far targets is very small, compared to post stimulation in which near targets appear to be maintaining a facilitation.



However simple contrasts in which each block was compared to the first did not show where the significance lay meaning no block was significantly different to the starting position. Looking at Figure 4-11 it is likely that the key differences stem from block 4.

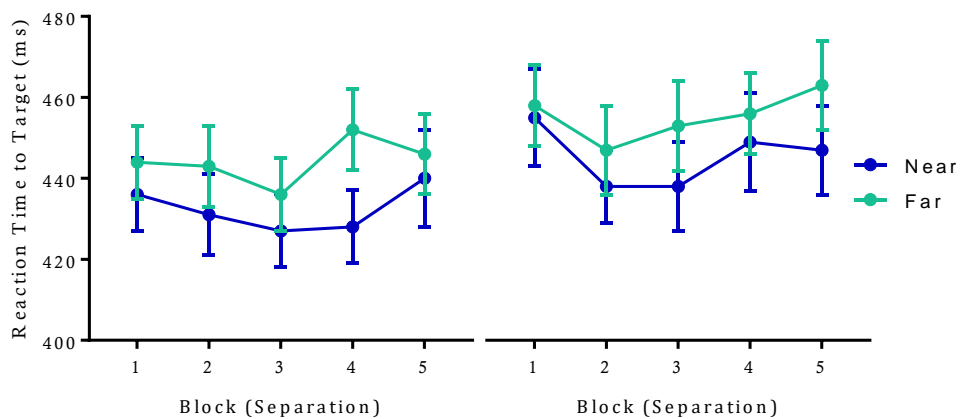


Figure 4-11: Interaction for Time\*Target Distance\*Block showing pre-stimulation on the left. Difference between near and far targets changes depending on amount of separation and receiving anodal stimulation.

Similar to what was found in the sham condition, a main effect of Block was observed,  $F(4,92) = 3.42$ ,  $p = .01$ ,  $\eta_p^2 = .13$ , with simple contrasts showing that overall reaction times to targets were significantly faster at 2-4 ( $p = .04$ ) and 4-6cm ( $p = .04$ ) of separation than when they were together. However the lack of a significant interaction between Block and Timeofstim, suggests that (regardless of target distance) anodal stimulation did not alter overall reaction times as the hands separated. Furthermore, no interaction was found between Targetdistance\*Block,  $F(4,92) = 1.036$ ,  $p = .39$ ,  $\eta_p^2 = .04$ . Additionally the three-way interaction adding in target distance was only marginally significant.

There was no main effect of Modality suggesting overall target reaction times did not differ depending on which hand they were in line with,

$F(1,23) = 2.66, p = .12, \eta_p^2 = .10$ . Furthermore the difference between near and far targets was not modulated depending on Modality as no significant interaction with Targetdistance was shown,  $F(1,23) = 2.01, p = .17, \eta_p^2 = .08$ . Nor was there an interaction observed for Timeofstim and Modality showing that reaction times to each hand did not differ as a result of stimulation,  $F(1,23) = 2.71, p = .11, \eta_p^2 = .11$ . Furthermore, the interaction for Time\*Modality\*Targetdistance also produced a non significant result highlighting that stimulation did not affect the NHE differently for each hand modality,  $F(1,23) = 1.28, p = .30, \eta_p^2 = .05$ . Lastly, the four-way interaction term was non significant, ( $F(4,92) = .305, p = .87, \eta_p^2 = .01$ ).

In summary, near targets were always responded to faster than far targets, both pre and post anodal stimulation. However it was expected that the difference between the two target distances might change post-stimulation, but this was not found. It was also expected, as with sham, that the difference between near and far would change as the hands separated, again this was not found. However, anodal stimulation did influence this, with results indicating that the large difference between near and far at block 4 pre stimulation changes post stimulation to be much smaller, while a larger difference is then seen at block 5 instead. Lastly, no changes between modality were seen in relation to the difference between near and far targets suggesting that the application of anodal stimulation did not bias one sensory input over another.

### *Cathodal Analysis*

As with the anodal condition, it was expected that Targetdistance and Timeofstim would show main effects and a significant interaction. Also that stimulation would change the difference between near and far as the hands separated, and possibly affect hand modalities differently.

There was a violation of sphericity for Block,  $X^2(9) = 26.35, p = .002, \epsilon = .61$ , and the Time\*Targetdistance\*Block interaction,  $X^2(9) = 23.96, p = .004, \epsilon = .64$ , therefore the greenhouse-geisser correction was applied.

Unlike in the anodal condition, no main effect of Timeofstim was found for cathodal stimulation,  $F(1,23) = 1.29$ ,  $p = .27$ ,  $\eta_p^2 = .05$ , suggesting that reaction times did not change post-stimulation. There was also no main effect of Timeofstim\*Targetdistance further supporting that stimulation did not change the difference between near and far targets,  $F(1,23) = .18$ ,  $p = .67$ ,  $\eta_p^2 = .01$ .

No main effect of Modality was found, however there was a significant interaction shown for Timeofstim\*Modality,  $F(1,23) = 5.53$ ,  $p = .03$ ,  $\eta_p^2 = .19$ . The means show that prior to stimulation reaction times for the visual hand were faster, but post-stimulation proprioceptive hand targets were quicker (see Figure 4-12). Looking at the Timeofstim\*Modality\*Targetdistance interaction however showed no significant interaction meaning that the difference between near and far targets did not change, but the average reaction times for each hand did post-stimulation.

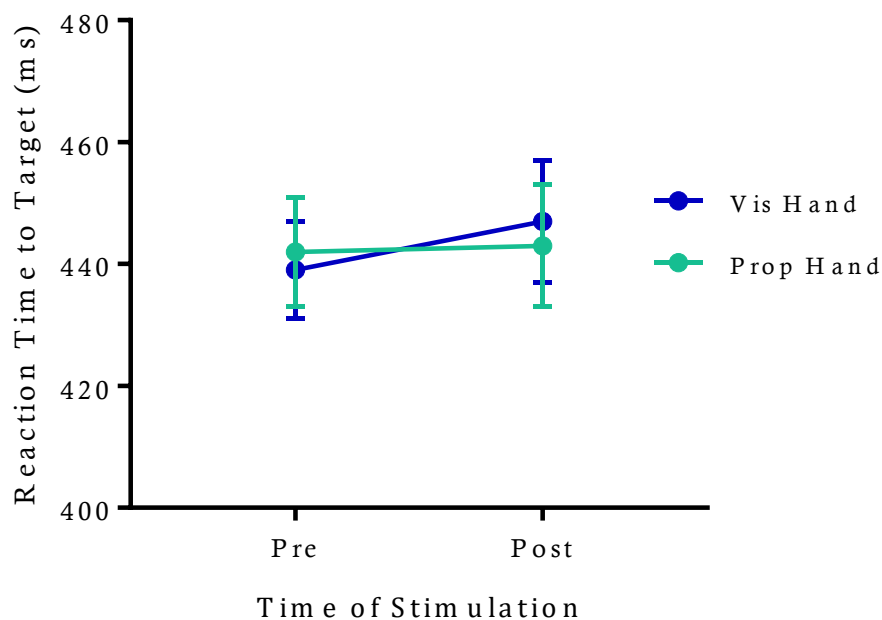


Figure 4-12: Time and Modality interaction. Significant change in RT's to targets to each hand depending on application of cathodal stimulation. Decrease in visual hand RT's post-stimulation.

Significant main effects were also observed for Target Distance,  $F(1,23) = 62.89$ ,  $p < .001$ ,  $\eta_p^2 = .73$ , and Block,  $F(2.45,56.43) = 3.154$ ,  $p = .04$ ,  $\eta_p^2 = .12$ , however no interaction between the two was shown. Planned simple contrasts showed the differences to lie at block 2 ( $p = .01$ ). All other interactions were non significant with the exception of the four-way interaction of Time\*Modality\*Targetdistance\*Block,  $F(4,92) = 4.16$ ,  $p = .004$ ,  $\eta_p^2 = .15$ . Planned simple contrasts highlight significant differences at block 4 and block 5 compared to block 1. Figure 4-13 shows blocks 1, 4, and 5 RT's for each hand, pre- and post-stimulation. Difference between near and far targets changes post stimulation for the visual hand in block 5 compared to the hands together condition (block 1). Block 4 shows a decrease in the difference between near and far targets for the proprioceptive hand post-stimulation.

In summary, the results of the cathodal condition did not show an overall main effect of Timeofstim, nor an interaction with target distance suggesting that RT's were not significantly different post stimulation overall, however the 4-way interaction suggests that the difference between near and far targets changed depending on modality, amount of separation and stimulation. Specifically, an NHE for the proprioceptive hand was nullified at 6-8cm of separation, whereas for the visual hand the NHE increased at 8-10cm, after receiving cathodal stimulation.

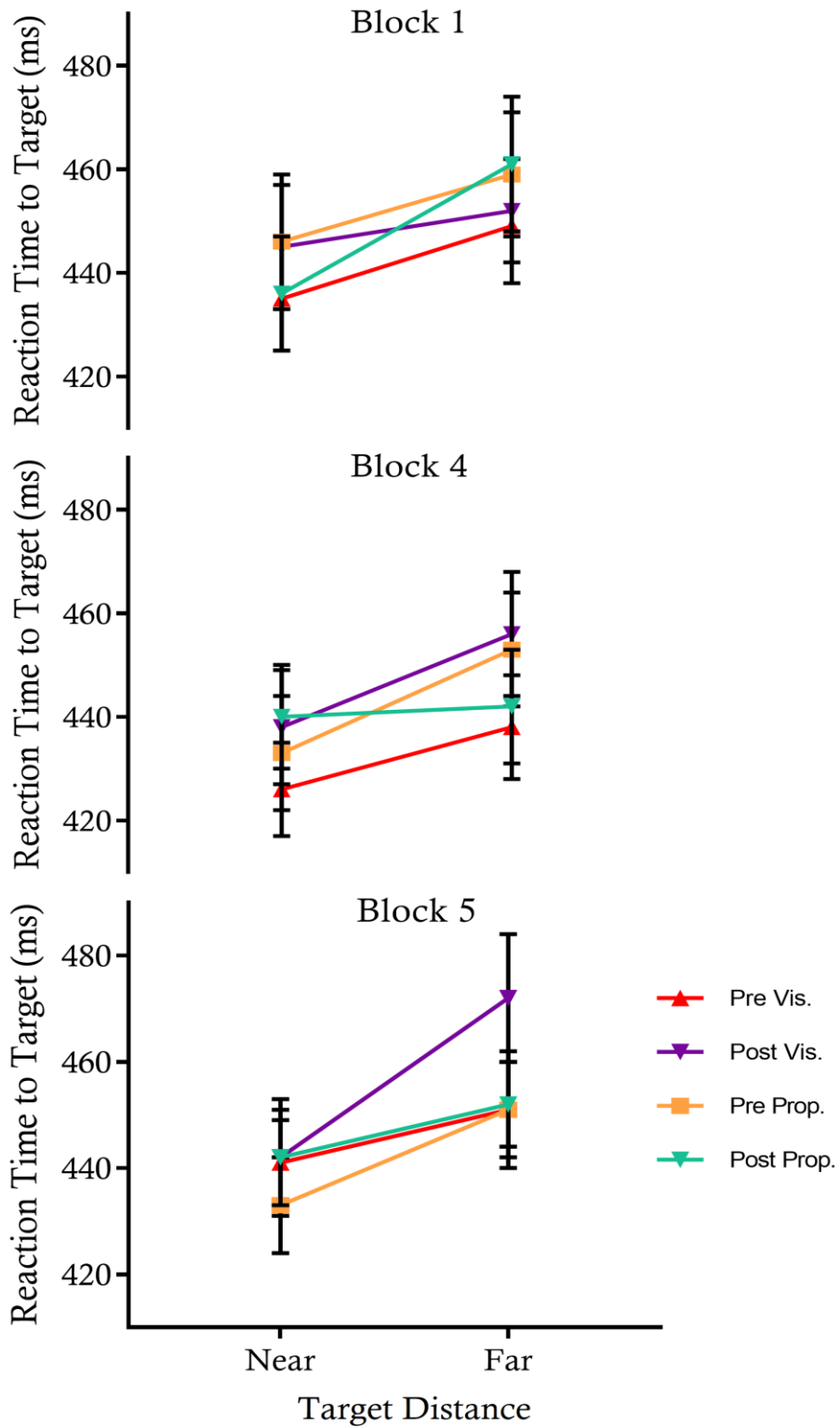


Figure 4-13: Four-way interaction showing change in effect of cathodal stimulation at blocks 4 and 5 compared to 1. Block 4 post prop shows no difference between near and far targets compared to block 1. Block 5 shows slowing of far target RT post vis.

Table 2: Summary of key results from main analysis

<b>Sham</b>	<b>P-value</b>
Timeofstim	.94
Targetdistance	<.001
Timeofstim*Targetdistance	.44
Targetdistance*Block	.63
Targetdistance*Modality*Block	.16
Timeofstim	.03
Targetdistance	<.001
Timeofstim*Targetdistance	.51
Targetdistance*Block	.39
Timeofstim*Targetdistance*Block	.045
Targetdistance*Modality*Block	.30
Targetdistance*Modality*Block*Timeofstim	.87
Timeofstim	.27
Targetdistance	<.001
Timeofstim*Targetdistance	.67
Targetdistance*Block	.50
Timeofstim*Targetdistance*Block	.60
Targetdistance*Modality*Block	.55
Targetdistance*Modality*Block*Timeofstim	.004

### *HIDSEP Analysis*

Reaction times to near and far targets for HIDSEP (at the end of each adaptation when the visual hand became hidden while modalities were separated) were analysed using ANOVA. Within subject variables were stimulation polarity, hand modality (whether targets appeared in line with the real hidden hand or where the visual hand had previously been), target distance (near or far), and time (pre or post stimulation).

Results of the ANOVA showed no main effects of Polarity, Modality, or Time, ( $F(1,474, 33.908) = .177, p = .77, \eta_p^2 = .008$ ;  $F(1,23) = 2.97, p = .099, \eta_p^2 = .114$ ;  $F(1,23) = 2.003, p = .17, \eta_p^2 = .08$ ) but did show a main effect for target distance,  $F(1,23) = 18.694, p < .001, \eta_p^2 = .448$ . This suggests that overall near targets were responded to faster than far targets ( $M = 433.18, SE = 7.99$ ;  $M = 444.01, SE = 8.61$ ) but that there was no effect of stimulation polarity, or stimulation overall as no significant changes were observed between pre and post sessions. Critically there was no significant difference between targets in line with the real hand and those in line with the previous visual hand location suggesting that the removal of visual information did not give significant priority back to the real hand location, and that potentially the previous visual information still elicited a priority zone.

There was no significant interaction between Polarity and Modality ( $F(2,46) = .161, p = .852, \eta_p^2 = .007$ ), Polarity and Targetdistance ( $F(2,46) = .289, p = .750, \eta_p^2 = .012$ ) Modality and Targetdistance ( $F(1,23) = .035, p = .835, \eta_p^2 = .002$ ) nor a three way interaction between them ( $F(2,46) = .138, p = .872, \eta_p^2 = .006$ ). Additionally there was no significant interaction for Polarity and Timeofstim ( $F(2,46) = 1.004, p = .347, \eta_p^2 = .042$ ), Modality and Timeofstim ( $F(1,23) = .040, p = .844, \eta_p^2 = .002$ ), nor a three way interaction ( $F(2,46) = .505, p = .607, \eta_p^2 = .022$ ). There was also no interaction shown for Targetdistance and Timeofstim ( $F(1,23) = 3.526, p$

=.073,  $\eta_p^2=.133$ ), Target distance, Polarity and Timeofstim ( $F(2,46) = .716, p = .494, \eta_p^2=.030$ ), Modality, Targetdistance, and Timeofstim ( $F(1,23) = 1.197, p=.285, \eta_p^2=.049$ ), nor was there a four way interaction for Polarity, Modality, Targetdistance and Time ( $F(2,46) = .271, p=.764, \eta_p^2=.012$ ). These results show that removing visual input of the hand did not significantly alter the NHE between the two modality locations, nor did stimulation polarity of any kind have an effect. It was expected that an interaction between target distance and modality might be found due to the removal of visual information however no differences between the two target hand locations was shown.

### **Questionnaire Data**

The questionnaire was administered after each reaction time session, both before and after stimulation, each week. Therefore each participants completed the questionnaire 6 times. Participants rated the statements on a scale of -3 for strongly disagree to +3 for strongly agree. These scores were then averaged across questionnaire categories to give one score e.g. for ownership. Scores were then averaged across participants to give one score per category for each testing condition. For example, anodal stimulation will have two results, one for pre stimulation and one for post. To make the results clearer graphs will show a comparison between pre and post stimulation to highlight if stimulation created any changes per session.



### *Anodal stimulation*

In relation to ownership scores, the means suggest participants did feel they had ownership over the hand. Results of a paired samples t-test showed no significant differences between pre and post scores,  $t(23) = .341, p = .736$ . Mean scores for unusual sensations show a negative score suggesting participants did not feel their hand was different to normal. The results of the paired t-test showed no significant differences between pre and post ratings,  $t(23) = 1.163, p = .257$ . These suggests that anodal stimulation did not significantly alter feelings of ownership or sensations over the virtual hand. See Figure 4-14. Participants were also asked if they felt their hand was moving. As illustrated by Figure 4-14 participants on average rated this negatively suggesting they were unaware that the hand was moving slowly.

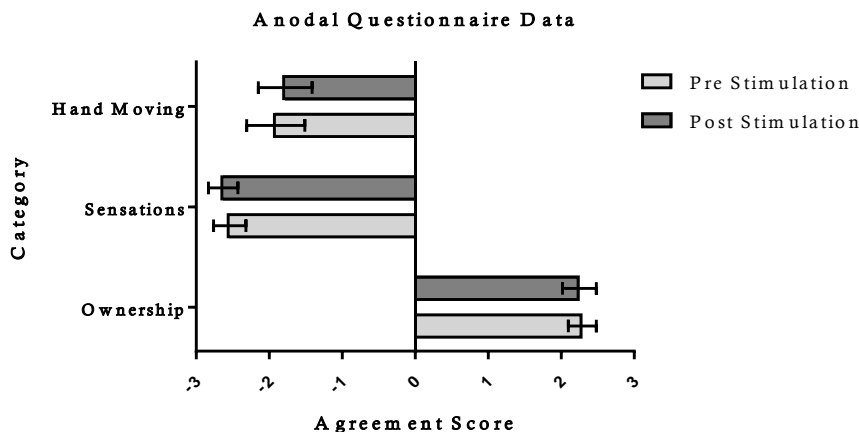


Figure 4-14: negative scores for hand moving and sensations suggests they were not aware of the hand moving or felt unusual sensations, whereas positive ownership scores indicate they did feel ownership over virtual hand.

### *Cathodal Stimulation*

For ownership ratings the means suggest participants did feel ownership over the virtual hand both before and after stimulation. A paired samples t-test revealed no significant differences between pre and post scores,  $t(23) = -.416, p = .682$ .

Ratings for unusual sensations suggest participants did not feel anything unusual before or after stimulation. The t-test results showed no significant differences between conditions,  $t(23) = -1.093, p = .286$ .

Ratings for whether the hand was moving suggest participants were again unaware that the hand had moved during the adaptation stage.

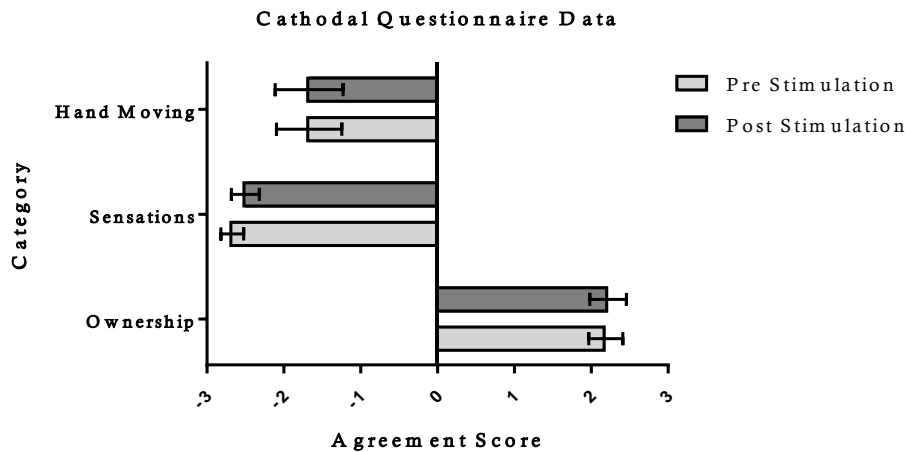


Figure 4-15: cathodal questionnaire results showing negative scores for hand moving and sensations, and positive scores for ownership, similar to anodal.

### *Sham Stimulation*

The means show that participants agreed that they felt the virtual hand was theirs, and didn't experience any unusual sensations. In line with predictions, a paired samples t-test showed no significant differences between pre and post stimulation for ownership,  $t(23) = .741, p = .467$ , nor unusual sensations  $t(23) = 1.142, p = .266$ . Additionally, looking at the average scores, participants were unaware that their hand was moving.

Table 3: summary table for means (and standard error) for each condition, pre and post. Hand Moving refers to did they feel their hand was moving. Negative scores indicate they did not notice it moving.

<b>Pre</b>	<b>Ownership</b>	<b>Unusual Sensations</b>	<b>Hand Moving</b>
Anodal	2.29 (0.19)	-2.54 (0.22)	-1.91 (0.40)
Cathodal	2.19 (0.22)	-2.67 (0.15)	-1.67 (0.42)
Sham	2.38 (0.17)	-2.64 (0.13)	-1.73 (0.43)
<b>Post</b>			
Anodal	2.25 (0.23)	-2.63 (0.20)	-1.78 (0.37)
Cathodal	2.22 (0.24)	-2.50 (0.18)	-1.67 (0.44)
Sham	2.29 (0.22)	-2.70 (0.11)	-1.64 (0.42)

#### **Hand Estimation Data**

At the end of each session (both pre- and post-stimulation) participants kept their hand hovering whilst they viewed a red arrow gradually move across the top of the screen from the right corner. They were asked to verbally state ‘stop’ when they believed the arrow was in line with the middle of their hand (no visual hand information was available at this point). This data allowed us to convert the pixel number in to a percentage of the distance between the visual hand location and the real hand. Results showed a similar pattern across each stimulation condition with hand position being perceived as 60% towards the visual hand, Table 4 shows exact values.

Table 4: Hand location estimation data across each stimulation condition. Shows percentage of distance hand was perceived to be between the last visual location and that of the real hand.

<b>% distance away from real hand</b>	<b>Pre</b>	<b>Post</b>
Anodal	56.81	59.52
Cathodal	60.38	58.72
Sham	60.33	61.08

## Discussion

### *Primary results*

In the sham condition the significant interaction between stimulation time and hand modality was unexpected as sham stimulation should not have altered performance creating a change post-stimulation. However this interaction could be the result of practise effects or participant awareness of their real hand position. By the time of the post-stimulation session the participant would have completed the spatial separation adaptation at least 6 times, plus a practise go. Therefore this could have meant the participant was more aware of their real hand position, consciously or otherwise, resulting in better reaction times to targets appearing near the real hand. Having knowledge of the hidden hand location has not been investigated and is unknown what effect this might have on the effectiveness of the NHE. The result here could be evidence that awareness of the unseen hand influences reaction times. Previous paradigms in which the hand is hidden from view have all involved the participant being aware of where their hand is, either through being asked to place it under a table or not having a conflicting visual hand present. Illusions in which the hand is covertly moved have not been fully explored in relation to the NHE.

Following on from this, the Timeofstim\*Modality\*Block interaction could be significant due to similar reasons. If the proprioceptive hand is gaining a stronger facilitation from awareness/repetition of the task, then this also seems to affect what happens to reaction times as the hands separate. This is evident at 4-6cm of separation showing faster reaction times for the proprioceptive hand sooner than before (pre-stimulation). This is further supported by the visual hand receiving less of a facilitation than pre-stimulation, potentially illustrating the trade-off between vision and proprioceptive inputs. If the participant becomes more aware of their real hand then the facilitation previously experienced by the visual hand could diminish slightly.

Alternatively there is another explanation. Sham stimulation should not modulate cortical activity, however perhaps this is not evidence of the stimulation creating changes, but the effect of time, specifically the effect of completing the adaptation over and over. The real hand is constantly changing position, starting in line with the visual hand and gradually moving rightwards. This could be creating an expansion in peri-personal space across the workspace rather than in the direction of far targets. This would result in there still being a difference between near and far, but also changes in reaction times across the blocks. For example, the results showed that in the first session (prior to stimulation, and before repeated exposure to the adaptation) by block 3 (4-6cm) reaction times are the same as they were at block 1, which could indicate the lesser influence of proprioception compared to the facilitation observed for the visual hand. However at the same distance in the second session block 3 is faster. This could be demonstrating that as the hands separate in to this newly expanded peri-personal space, this position is registered as the centre of that space and therefore targets nearest this position are processed relatively faster. This could also explain the opposite result observed in the visual hand with targets appearing when the hands are 4-6cm apart being responded to slower than pre-stimulation. These targets are now relatively further away from the centre of peri-personal space. However they likely do not get slower because of the higher influence of vision in general.

With the overall pattern of results showing both near and far targets slowing after block 3, this could illustrate the creation of two zones of peri-personal space, one around each hand, rather than the initial expansion.

#### *Anodal summary*

Similar to what was observed in the sham condition, after anodal stimulation larger differences between near and far targets were created at blocks 3 and 5. Interestingly, after stimulation the NHE was very small when the hands were together, perhaps illustrating that sensory information was more strongly telling the participant that their hand was

located closer to block 3, i.e. closer to where they believed their hand to really be, meaning the location of targets at block one was relatively further from the location of their hand.

It was hypothesised that anodal stimulation might enhance the integration of visual and proprioceptive inputs resulting in two distinct zones of peri-personal space being created sooner. This might be evident in reaction times slowing down sooner than block 3 demonstrating a switch from an expansion of space to two zones. It could be argued that this was seen in the results as the largest difference between near and far targets pre-stimulation is at block 4, whereby after stimulation block 3 has a larger NHE than block 4.

#### *Cathodal summary*

The significant four-way interaction for the cathodal session would suggest that the difference between near and far targets changes depending on hand modality, application of stimulation and the amount the hands have separated. Planned contrasts comparing each condition to the first highlighted differences to be at block 4 and 5. The graphs show that post-stimulation the NHE gets smaller as the hands begin to separate for the proprioceptive targets, but larger for the visual hand targets. When the hands are fully separated targets in line with the real hand barely show a facilitation for near targets, whilst the visual hand shows a large facilitation. So why would cathodal stimulation, which should inhibit the PPC show a stronger facilitation for vision when theoretically two zones of peri-personal space have been created? If the visual hand is considered the new 'tool' then this could mean that since the 'tool' was being used, the area around it is immediately more functional than the area around the real hand. This could be evident as an increased processing for near stimuli. Since the PPC is thought to integrate multisensory information perhaps cathodal stimulation disrupted this ability and therefore initiated a stronger reliance on one sense rather than incorporating both, in this case vision. This could have resulted in proprioceptive information being

neglected whilst the visual hand was deemed more important and functionally relevant.

At block 5 there was little difference between RT's for each hand modality prior to stimulation, however after the application of cathodal stimulation it appears that the visual hand is receiving preference as indicated by a larger facilitation for near targets. This evidence contradicts what was seen in the sham condition in which the proprioceptive hand received faster reaction times in the post-stimulation session. If repeating the adaptation process was the cause of increased proprioceptive awareness in sham, then could cathodal stimulation inhibit this? If participants become less aware of their real arm position this could explain the stronger facilitation for near visual hand targets. At block 5 the hands are fully separate, if proprioceptive hand information is inhibited then additional visual information would no longer assist reactions to proprioceptive hand targets due to lack of overlap. It is therefore plausible that proprioceptive information is of no benefit to the task after the application of cathodal stimulation, and instead the visual information has aided target perception whilst the hands remained closer.

### *TOGDISP*

TOGDISP in which the hand was stationary, resulted in some unexpected findings, namely in the sham condition no difference between targets in line with the hand and those displaced to the right, and a significant interaction of Timeofstim and Targetdistance for the sham condition.

This could be the result of several factors. First, it could indicate that near targets receive their facilitation not from the hand, but from the body, meaning that targets presented distally rather than laterally show this pattern of facilitation. On the other hand the distance laterally from the near hand target to the other 'near' target was smaller than the distance from the near hand target to the far hand target. Therefore it could be argued that the near hand target would be responded to fastest (2cm), followed by the near target displaced to the right (10cm), then the far hand

target (15cm), and lastly the far displaced target would be responded to slowest (18cm). The means show this was not the case however, with the largest difference between near and far being for the hand condition, and therefore the far hand target showed the slowest reaction times. However this does suggest that targets in line with the hand showed a stronger facilitation (relative to far) and also shows support for the m-cell account in demonstrating a trade-off between near and far targets.

Additionally, evidence from the pilot in which no facilitation was found for the block condition would suggest that proximity to the body can not create the same facilitation or this would have been observed for the block condition. Therefore it is more probable that it was proximity to the hand that created a facilitation rather than the trunk/body. If the m-cell account is to be believed then this could explain why there was a smaller difference between the near and far displaced targets, but still an NHE due to their proximity to the hand. In future a larger workspace could test this further, however the distance between the displaced and hand targets was restricted in the present study due to the size of the MIRAGE.

The significant interaction for Timeofstim and Targetdistance in the sham condition for TOGDISP illustrated that after stimulation the difference between near and far targets was significantly less than before. One possible explanation for this was that the post-stimulation session occurred after the participant had also completed the main stage of the experiment in which the adaptation may have created an expansion of peri-personal space. Therefore for post stimulation TOGDISP all targets may have benefited from this expansion, meaning near targets did not receive the same relative facilitation as before. This reduced difference between near and far post-stimulation can also be seen in Figure 4-5 for anodal stimulation.

The key result from the anodal TOGDISP was the Timeofstim\*Hand\*Targetdistance interaction. Figure 4-5 illustrates that the displaced no hand targets did not show a facilitation for near targets pre-stimulation, but did post-stimulation. It also shows that the NHE was



reduced for hand targets. This could be evidence of the changing proprioceptive information from the adaption being encoded telling the brain that the hand could be in any of these locations across the workspace, and therefore broadening the area of peri-personal space meaning displaced targets receive the same facilitation as those near the visual hand in TOGDISP post stimulation/adaptation.

Interestingly, in the cathodal condition there was a significant 4 way interaction of Timofstim\*hand Visibility\*Hand or no hand targets\* Targetdistance. When thinking about the experiment as a whole, this 4-way interaction might be expected. For example, if cathodal stimulation disrupts the sensory integration of both visual and proprioceptive information as the hands are separating in the main stage, the brain may have to rely on vision alone. This is perhaps more evident in the results for the post stimulation TOGDISP results which occurs after the hands have undergone the separation adaptation repeatedly. The results show that when the hand is visible it maintains a strong NHE, while the displaced targets do not. Second, when vision of the hand is removed the effect is nullified. Furthermore, if we look at targets that were not in line with the hand we can see that there was not a clear facilitation for nearer targets, pre- or post-stimulation. This could indicate that cathodal stimulation disrupted the integration of proprioceptive information, and also appears to have narrowed the area around the visual hand that prioritises near targets compared to both the anodal and sham conditions which both did not see a main effect of Hand, unlike cathodal.

These results firstly demonstrate that a NHE was found when the hand was invisible suggesting that proprioceptive information regarding hand position was enough to elicit an effect (in both sham and anodal). Second, that cathodal stimulation somehow disrupts this effect. Additionally the increase in a NHE for the displaced targets after anodal stimulation could suggest that it does the opposite of cathodal, however for the hand targets an increase in the difference between near and far was not observed for the anodal condition.

This modulation to the PPC could be reducing the ability to maintain and update the position of the limb when visual information is not also available (Avenanti et al., 2012; Inoue et al., 1997). After receiving cathodal stimulation participants then placed their hand within the MIRAGE and completed the visual and hidden conditions in a counterbalanced order. However between conditions participants could remove their hand to rest and therefore when placing it back in for the hidden condition they would have had no clue as to the veridical position. However the location of the targets would have informed them where their hand likely was. The fact that this disruption and change in the NHE happened anyway would suggest that top-down knowledge of hand location did not influence the processing of peri-personal space. This would suggest both an important role for vision, and the influence of bottom-up factors in creating an up-to-date reference frame for peri-personal space supporting previous research (Henrik Ehrsson et al., 2004; Tsakiris et al., 2007). Furthermore, this result would suggest that cathodal stimulation caused a substantial interference encoding proprioceptive input, especially since the hand was positioned very close to the midline, which usually results in proprioception having greater weighting than vision (Van Beers et al., 1998). Since we're seeing a reduction of the NHE in the hidden condition after cathodal stimulation this would indicate a substantial disruption.

The results of TOGDISP support what was found in the main experimental stage as in both cases cathodal stimulation appears to significantly disrupt proprioceptive contributions to the NHE as shown by hidden TOGDISP, and the much larger NHE for the visual hand in the main stage after cathodal stimulation whilst neglecting the real hand targets. The difference in methods between these stages does suggest that cathodal stimulation to the PPC is disrupting proprioception rather than perhaps choosing to rely on vision unable to integrate the signals. No visual information was presented during the hidden TOGDISP condition yet still no NHE was found for targets in line with the hand, thus suggesting that stimulation is preventing the up-to-date representation of

peri-personal space, perhaps by being unable to compile accurate limb position estimates.

### *HIDSEP*

The results of HIDSEP at the end of the adaptation revealed there was no significant difference between the two hand modalities across all stimulation conditions. It was hypothesised that this could occur, with the reasoning being that any extension of peri-personal space (to encompass the visual hand) would still be present after the removal of visual information for several minutes. This temporary adaptation has been shown in tool use studies after the tool has been removed showing that peri-personal space doesn't immediately snap back to its pre-adaptation limit, but likely restores itself gradually (Farnè & Làdavas, 2000). This also provides evidence that peri-personal space shows plasticity. Further investigation of this could be done by having participants respond for a longer period of time after the visual input is removed to measure how long these changes last for. However due to a NHE being observed in the TOGDISP no hand condition it is possible that it was not the visual input that was responsible for the prolonged facilitation, for example the influence of the trunk or the proximity to the real hand location.

### *Questionnaire Data*

None of the stimulation polarities significantly changed scores on the questionnaires investigating ownership, unusual sensations, and awareness of hand movements. Therefore this indicates that the spatial separation between the two senses did not impair ownership (scores were always positive), nor did it create unusual sensations. Additionally the covert nature of the adaptation worked as participants scores reflected that they did not believe their hand was moving. This lack in changes of ownership is at odds with the reaction time results which showed changes in the processing of peri-personal space. It suggests that the changes in the NHE are dependent on changes to peri-personal space, but not to the body image or schema. Although these two concepts are not the same thing, it is thought that the representation of space around the body is reliant on

the body schema (Cardinali et al., 2009). It's possible that our ownership questionnaire did not adequately reflect the body schema, or that the amount of separation between the two hands was not sufficient to disrupt a sense of ownership, but was enough for the PPC to detect incongruence for the reaction time task.

#### *Hand Location Estimation*

No changes in where participants believed their hands to be were seen across the different stimulation conditions. This indicates that modulation to the PPC did not alter how the visual and proprioceptive inputs were being integrated, giving one more weighting than normal. Prior to stimulation participants estimated their hands to be 60% of the distance between the two hands, favouring the visual hand. This is in line with previous research showing that people use both visual and proprioception to form a representation somewhere in between (Ratcliffe & Newport, 2016). This result however is not consistent with the findings from the TOGDISP, nor the main experiment, which suggested cathodal stimulation was interfering with the processing of proprioceptive information. Therefore it would be expected that hand estimates would be closer to the visual hand post-stimulation, however this was not found.

When considering the reliability of the results it's important to consider the variable nature of tDCS which may of course affect replicability of results. It's been shown that stable effects even within the same participant have not been reliably found (Dyke et al., 2016). However our results do support previous neuro stimulation research in which disruption to the PPC has effected the processing of near hand space (Bjoertomt et al., 2002) and updating sensorimotor representations (Rushworth & Taylor, 2006). Therefore the observed changes as a result of cathodal stimulation in the processing of near hand targets highlight further opportunities for investigating neuromodulation of the PPC.

In summary, the results presented here demonstrate that cathodal stimulation impairs the NHE, particularly for cases in which visual information is not available, meaning the real hand location is not able to

generate the same near target facilitation. This is potentially because of disruption to the PPC in updating the location of the limb in space, disrupting its ability to compensate for sensory incongruences, or by impairing the ability of peri-personal space to expand. Perhaps it affects all three functions, regardless these results show that the PPC is critically involved in the processing of peri-personal space particularly when sensory inputs are incongruent. Furthermore anodal stimulation may facilitate the NHE in identifying two effectors more quickly, however this is less clear. Lastly, this experiment proposes that repeated movements in the same area of space expands peri-personal boundaries illustrating its adaptive nature.

## Chapter 5 The Effects of Appearance Changes to the Hand on the Processing of Peri-hand Space.

The NHE has been shown to rely partly on vision of the hand, either by preparing the limb for action by prioritising the magnocellular pathway (m-cell) (Goodhew et al., 2015) or through increasing responses from bimodal neurons (Graziano and Gross, 1993). So far this thesis has demonstrated that a virtual representation of the hand can create a NHE but a block does not, therefore the question remains how realistic does the hand need to be in order to elicit a NHE. Neuroimaging evidence suggests that viewing a fake limb results in different neural activation compared to viewing a real limb (Perani et al., 2001). In the study participants viewed a real hand performing a reaching task along with low fidelity and high fidelity virtual hands. fMRI was used to measure oxygen levels as they viewed these different conditions. They found that both virtual hand conditions resulted in less activation than when the real hand was observed. The low fidelity hand still had roughly shaped digits but did not resemble a hand in colour or textural detail, while the high fidelity hand was much more similar to the observed real hand. These results would suggest that viewing a fake hand does create a significantly different neural response, even with reasonably high fidelity.

However other research has shown that even a fake hand can modulate the representation of peri-hand space. When placing a fake hand in the same natural position as in the real hand condition (while the real hand had been retracted out of sight) similar patterns of activation were observed for the appearance of near hand targets. This suggested that activation in the parietal cortex was modulated by the visual position of the hand (fake or real), whereas when the real hand was occluded from view activation was much less (Makin et al., 2007). These pieces of evidence suggest that the brain is able to identify differences, however subtle, between a real and fake hand but also that an item resembling a hand can influence activation of peri-hand space. However from this

research it is still unclear what causes this if the brain is also adept at recognising a fake. It would appear that a fake hand can influence the processing of peri-personal space but perhaps this does not disrupt the representation of the body, but rather add to it.

Further studies showing differences in results depending upon vision of the limb demonstrated that patients with left tactile extinction were poorer at detecting left hand taps when a visual event was simultaneously presented near the right hand, more so when the right hand was visible (Làdavas, Di Pellegrino, Farnè, & Zeloni, 1998). When the hand was occluded the visual event had less success at extinguishing the detection of a left hand tap (Mattingley, Driver, Beschin, & Robertson, 1997). All these examples highlight the important role of vision, specifically vision of the hand, in how the space around the body is processed.

Hand fidelity has also been shown to impact on performance in a reaching task (Durlach, Fowlkes, & Metevier, 2005). The study showed that by reducing the realism of the hand in the VR setting participants performed slower and experienced increased disorientation. This showed that changes in hand fidelity, specifically within a VR setting, alter the way the participant interacts with the effector. The authors argued that the reduction in similarity between the virtual hand and the real limb interfered with promoting visual capture.

Visual information can be particularly influential if it is combined with synchronous feedback in another sensory modality such as touch. This is evident in rubber hand illusion (RHI) studies in which a fake hand may be embodied as a result of synchronous but not asynchronous visual and tactile feedback (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008; Tsakiris & Haggard, 2005; Tsakiris et al., 2007). As a result of this illusion some researchers have suggested that anything may be embodied, corporeal or not, as long as there is synchronicity between two or more senses. This 'bottom-up' approach was further tested using a table in place of a realistic rubber hand (Armel & Ramachandran, 2003). Results showed a small increase in skin conductance responses for the

synchronous stroking condition. The authors took this as evidence that anything can be experienced as part of one's body if there is a strong correlation between sensory modalities. This argument would suggest that appearance alterations to the hand may not be sufficient to stop ownership being transferred to a virtual hand however they do suggest that synchronous vision and touch to an altered effector may help participants to accept something unfamiliar in to the body representation. On the other hand, research on visual capture has demonstrated that vision alone can also be very powerful. For example, work by Holmes, Crozier and Spence (2004) showed that viewing the left side of the body reflected in a mirror made the reaching movements of the unseen right arm significantly more inaccurate as a result of the incongruent visual information. Therefore vision alone may strongly influence our sense of limb position.

Rubber hand style illusions in which a fake hand or non-corporeal object are stroked in synchrony with the real hidden hand have evaluated whether changes in appearance of the hand influence perceived ownership and the strength of the illusion. Appearance can change in several dimensions, including shape, texture, and detail. Previous literature suggests that texture may not be as important a factor as shape. This was demonstrated by participants viewing either a hand shaped block or tabletop, with or without a natural skin like texture applied. Results showed a stronger RHI for the hand shaped block over the tabletop with added skin like appearance (Haans, IJsselsteijn, & de Kort, 2008). This suggests that resemblance in shape to the body part is more important in inducing a sense of ownership than textural appearance. However the results also showed a diminished RHI in the absence of the skin detail when the block was covered in a white glove. Conversely, further research has shown that participants are able to successfully embody a rubber hand that does not match their racial group (Farmer, Tajadura-Jimenez, & Tsakiris, 2012). Therefore it could be argued that both shape and texture influence the strength of the RHI and sense of ownership over limb, but to different degrees.



A further study investigated changes in sensory quality by stroking the participant's hands (real and fake) with soft or rough fabric (congruent or incongruent in terms of matching fabric) (Schütz-Bosbach, Mancini, Aglioti, & Haggard, 2006). Results showed incongruent visual and tactile stimulation (in terms of fabric used) did not affect the strength of the illusion, measured through a questionnaire and proprioceptive drift, highlighting that temporally synchronous stimulation is sufficient to induce a sense of ownership over the fake limb regardless of texture congruence, offering support to the 'bottom-up' theory (Armel & Ramachandran, 2003).

Other than the above evidence described, there is little other research that supports experience of ownership over non-corporeal objects (Tsakiris et al., 2010). It has been suggested that the brain has a specific process for identifying whether an object is corporeal or non-corporeal which perhaps partly relies on visuo-tactile sensory input (Tsakiris, 2008). On the basis of this the author conducted further research examining different degrees of hand fidelity on the experience of the RHI. Five items ranging from a hand sized (but not shaped) wooden block, to a prosthetic rubber hand. Middle range items included adding a thumb, followed by a wrist shape, and then finger length definition (with fingers still presented together, not as individual digits). Synchronous and asynchronous visuo-tactile stimulation was performed for each between measures hand group. Results showed that positive ownership scores were only found for the prosthetic hand and no other hand condition. A significant proprioceptive shift was also only observed for the rubber hand condition. The authors concluded that simple bottom-up sensory feedback was not sufficient to elicit feelings of ownership for non-corporeal objects and instead suggested that the object must structurally resemble the stimulated body part to be incorporated (Tsakiris et al., 2010).

In the majority of RHI studies proprioceptive drift is measured by having the participant estimate the location of their hand through using a ruler as a reference. By recording the distances at which participants believe their hand to be, the authors conclude a shift in the perception of the hand to

indicate a transfer of ownership to the fake hand. However, more recent evidence has suggested that drift and ownership are not correlated and are likely separate mechanisms (Riemer, Bublatzky, Trojan, & Alpers, 2015; Adbulkarim & Ehrsson, 2016). Therefore the NHE may provide a clearer measure of perceived limb position as shown by shifted receptive fields that move with the limb, or fake visual limb (Graziano et al., 2000). This may act as a more implicit measure as participants will not be directly thinking about their hand position when responding to targets, unlike the ruler estimation method. In the present study the limb remains in its veridical location. However if the visual representation of the hand is less realistic the NHE may become less reliable, only depending on the proprioceptive information and disregarding the suspect visual input.

Other research has proposed that bottom up factors alone are not enough to induce a sense of ownership, but are required to fit with a body model that evaluates postural, anatomical and spatial information (Costantini & Haggard, 2007; Ma & Hommel, 2015; Tsakiris et al., 2007). However Ma and Hommel (2015) highlighted that bottom-up factors may have been systematically underestimated due to many previous studies using static objects such as a rubber hand. They point out that a key difference between using a rubber hand and a virtual hand is the influence of visuo-motor bottom-up feedback, rather than just visuo-tactile. Visuo-motor synchronicity has been shown to contribute to a sense of ownership significantly more so than visuo-tactile synchronicity (Kokkinara & Slater, 2014). With this in mind, they designed a study to investigate whether a non-corporeal object could indeed be accepted as part of the body through use of visuo-motor manipulations using virtual reality.

In two experiments, one a 3D virtual balloon the other a 2D square, participants had control of the location, size and orientation of non-corporeal objects while their real hand was hidden from view. They predicted that if ownership was perceived over either object then bottom-up visuo-motor processes are sufficient in inducing ownership, and would provide evidence against the body model as neither object resembled a body part. They concluded that ownership was perceived for the virtual

effectors due to a significant main effect of synchronicity. However looking at their questionnaire responses, only 3 out of 7 questions did participants respond in agreement. So despite significant differences between synchronous and asynchronous conditions, the majority of questions were still scored as disagree in relation to ownership over the virtual effectors.

The above studies all highlight the importance of appearance in embodiment of a limb. Evidence that has shown changes in neural activity for fake versus real hands, bottom-up processes can enable embodiment, top-down processed can alter perceived ownership, and changes in activity for items appearing near a visual hand, fake or real. As highlighted by Ma and Hommel (2015) critical differences in methodologies may have influenced conclusions about how important fidelity of the limb is to transfer of ownership. The present study aims to overcome these issues by being able to solely investigate the role of hand fidelity with the use of MIRAGE which will allow spatial and temporal congruency between the real and seen hands, while manipulating the appearance of the hand.

Unlike previous research that has relied on measures of proprioceptive drift, the present study changed the appearance of the limb whilst keeping the real hand in the same location as the visually altered hand. With the hand in its veridical location participants viewed a virtual representation of their hand within the MIRAGE across 4 stages of fidelity. The virtual hand was first presented with less detail, similar to that presented by Haans et al (2008) in which skin textural detail was removed. Further conditions change the shape of the hand, first by reducing the detail of the digits and presenting a solid block colour hand with fingers together (similar to one of the conditions presented in Tsakiris (2010)), and second by removing one of the fingers so it appears as if the hand has only 4 digits.

It was hypothesised that with reduced fidelity the NHE may become less reliable than in the no manipulation condition as measured through reaction times to near and far targets, supporting previous evidence found

by Tsakiris et al (2010) that only the realistic hand would maintain ownership. However a NHE may still exist across all conditions due to the proprioceptive input (Reed et al., 2006), however this should become less reliable with a lower reliance on visual information. This may be shown through a significant interaction in which the difference between near and far target does change depending upon the appearance of the hand. Second, through the synchronous tactile and visual feedback the 4 digit hand would be successfully embodied as measured through ownership ratings.

If a reliable NHE is found with no difference across visual conditions this would suggest that a more generic hand, such as those used in VR, could still process peri-personal space in the same way as a detailed high fidelity version. It could also highlight that the primary factor preventing the perception of ownership across lower fidelity limbs in previous research is the spatial dislocation, rather than purely appearance.

## Methods

### Design

The experiment was investigating changes in appearance to the virtual hand by altering how realistic the hand appeared. There were four levels of fidelity, baseline, or 'BASE', in which no manipulation was added and the hand was a monochromatic live representation of the participants own hand; 'YEL' which showed the hand in block yellow colour with no textual detail; 'TOGETHER' in which the hand was block yellow but participants were asked to place their fingers close together so less hand shape detail was available; and '4DIGIT' hand. The 4DIGIT hand was also block yellow colour but through use of a rubber glove worn by the participant it was possible to make it appear as though they only had 3 fingers and thumb. During this stage an adaptation was also performed which involved the experimenter stroking both their fourth and (unseen) little fingers at the same time to elicit the feeling that their little finger had disappeared. The experimenter's finger stroking the invisible little finger was also not visible to the participant. The dependent variable in all 4 conditions was reaction times to targets that appeared near and far from the hands. These 4 conditions reduced the realism of the hand first by removing hand details (YEL) then by removing digit detail (TOGETHER) and finally by making the hand unrealistic by removing a digit (4DIGIT).

### Participants

Participants were recruited via advertising posters placed on and around the University of Nottingham's main campus. Exclusion criteria included a latex allergy. A total of 20 participants were recruited, 9 were male, with ages ranging from 18-27 ( $M=21.15$ ).

### Stimuli and Equipment

Target appearance and dimensions were exactly the same as in chapter 2. 100 targets were presented per appearance condition, 50 near and 50 far (distances were the same as in chapter 2).

The MIRAGE system which sends a live video recording of the participant's hand to the computer before sending an output image back allows for the manipulation of the image. In the present study it was possible to present the entire hand as a bright yellow colour while still allowing free movement by the participant (see Figure 5-1.)



Figure 5-1: YEL hand condition in which the participant's hand was in its veridical position and size whilst the whole hand appeared in a block yellow colour with no textural detail.

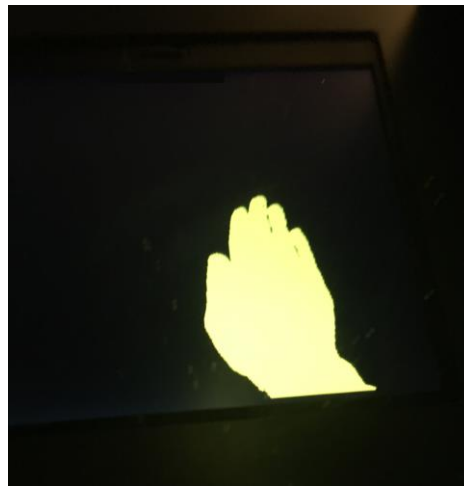


Figure 5-2: 'Together' hand in which participants kept their fingers together so only an outline remained rather than digit definition.

Figure 5-2 shows TOGETHER condition similar to that of Tsakiris et al. (2010) in which a hand shaped block was used showing fingertip lengths. This was the second step away from the real hand, no textural detail in addition to a reduced hand like shape.

For 4DIGIT stage participants wore a latex glove on their right hand. The glove was modified so that the little finger and down the right side of the glove were shaded out with marker pen. When this glove was then placed inside the MIRAGE the shaded parts of the glove were not visible, see Figure 5-3. Contrast adjustments were made for each participant to ensure the shaded sections were not creating any visual artefacts.

For 4DIGIT hand adaptation a questionnaire was verbally administered pre and post stroking of the hand. This comprised of 9 questions. Three pre questions included ‘The hand I see feels like it is my hand’, ‘It feels like I only have 3 fingers and a thumb’ and ‘the hand I see belongs to me’. After 30 seconds of stroking the little and fourth fingers participants answered 2 questions pertaining to ownership, 1 regarding unusual sensations and 3 relating to how their hand felt as it was being stroked e.g. ‘It felt like I was missing my little finger’. The full questionnaire can be found in appendix 6.



Figure 5-3: ‘4-digit’ hand in which the little finger is no longer visible. This happened as soon as the hand entered MIRAGE due to the glove being worn.

## Procedure

Participants placed their right hand within the MIRAGE and viewed it in four different fidelity conditions. Condition order was counterbalanced

across participants. During YEL participants saw their hand appearing bright yellow and were asked to place their fingers slightly spread apart so each digit was clearly visible. They were asked to then fixate on the green fixation cross that was presented continuously once their hand was in position, appearing in line with their middle finger approximately 8.5cm in away from the hand. Targets would then appear pseudo-randomly in either the near (~2cm) or far (~15cm) locations. With 100 targets to respond to each condition lasted for approximately 3 minutes 20 seconds. This procedure was then repeated for TOGETHER and BASE.

4DIGIT also involved the reaction time to target task but with the addition of the adaptation performed by the experimenter. This involved participants wearing the rubber glove and viewing their hand within the MIRAGE in which it appeared they did not have their little finger. At this point participants verbally answered the pre-adaptation questions rating how viewing the hand made them feel. The experimenter would then stroke both the invisible little finger at the same time as the fourth finger while the participant was instructed to watch and think about how their hand was feeling. The experimenter wore a black piece of cloth covering their middle finger so that it appeared that they were only stroking the fourth finger of the participant. During this adaptation both the experimenter's and the participant's hands appeared bright yellow. The fingers were stroked for 30 seconds before asking the participant what it felt like. If the adaptation was successful then participants would likely report that it felt like they did not have a little finger. Participants then verbally scored the post-adaptation questions regarding how their hand was feeling. The reaction time task was completed after the adaptation was complete.



## Results

### Reaction Time Data

Reaction times to near and far targets were collected for each fidelity condition, BASE, YEL, TOGETHER, and 4DIGIT. The hypothesis was that there may be a change in the NHE for conditions where the hand is less realistic compared to BASE.

Results of the repeated measures ANOVA highlighted a significant main effect of target distance,  $F(1,19) = 54.10$ ,  $p < .001$ ,  $\eta_p^2 = .74$ , showing that near targets ( $M=488.61$ ,  $SE=12.39$ ) were responded to significantly faster than far targets ( $M=507.31$ ,  $SE=12.24$ ). As for appearance condition no main effect was observed indicating that changes in the hands fidelity did not significantly alter reaction times to targets,  $F(3,57) = .32$ ,  $p = .81$ ,  $\eta_p^2 = .02$ . The interaction term also produced a non-significant result suggesting that the difference between reaction times to near and far targets was not dependent on changes in hand fidelity,  $F(3,57) = 1.12$ ,  $p = .35$ ,  $\eta_p^2 = .06$ . (Figure 5-4).

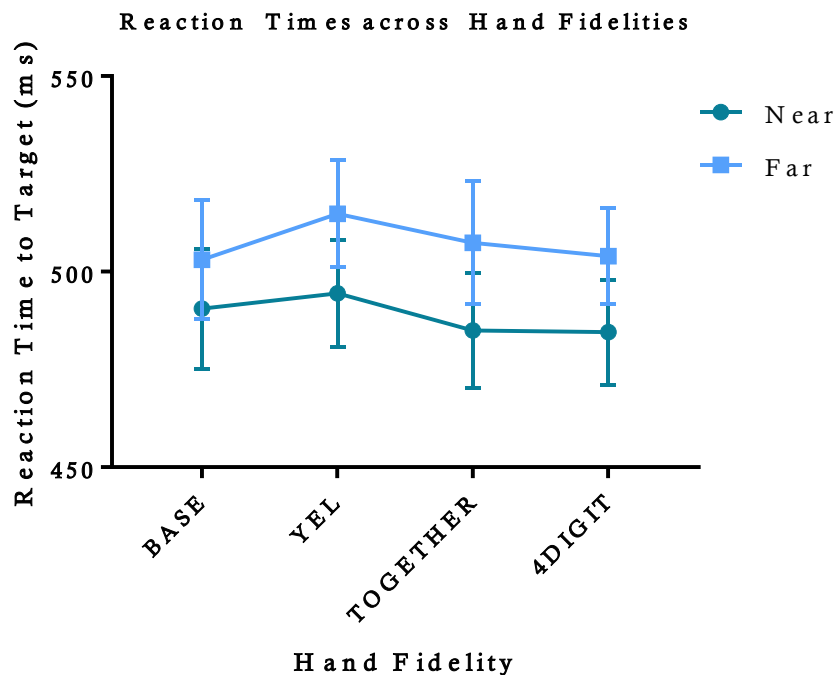


Figure 5-4: Graph shows significant main effect of target distance with faster reaction times to near targets across all hand fidelity conditions.

### Questionnaire Data

Questionnaire data were collected during the 4-digit hand condition both before and after stroking of the hand. The stroking was the same adaptation process used for the RHI with the aim of making it feel like only one finger was being stroked (when in fact two were) to help elicit the sensation that they had indeed lost their (invisible) little finger.

Participants answered questions whilst viewing their hand within the MIRAGE while wearing the rubber glove. It appeared that they only had 3 fingers and a thumb with the little finger not being visible. Questions 1-3 were asked upon initial viewing. These were to establish whether purely viewing the hand in this form elicit feelings of ownership over the hand and the feeling of missing their little finger. The further 6 questions evaluated perception of the hand post-stroking (see Figure 5-5).

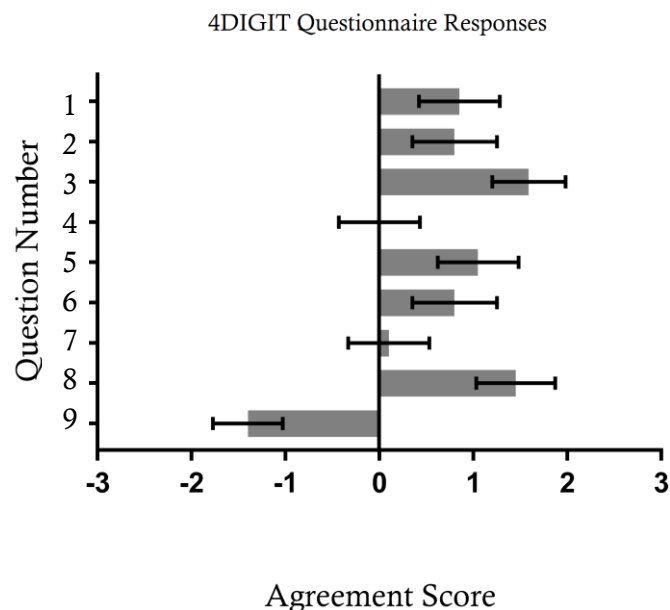


Figure 5-5: Questions pertaining to participants viewing the '4-digit' hand. Scored answers verbally using 7 point scale ranging from -3 for strongly disagree up to +3 for strongly agree. 1-3 asked pre-stroke. Results show participants maintained ownership.

Results showed a positive score for the pre-stroke questions highlighting agreement that they did feel the hand they were viewing belong to them and it felt like they only had 3 fingers. However these scores were close to 1 suggesting a small amount of agreement rather than full confidence in

their answers. Questions 4 and 5 evaluated the stroking adaptation. In reality the experimenter was stroking 2 fingers, both the fourth and little fingers concurrently. With the appropriate amount of spacing between the fingers an illusion should be created making it feel as if only one finger is being stroked. Participants were only able to see one finger being stroked. Results suggest that participants on average were unsure if only one finger was being stroked, but when asked if more than one finger was stroked, answered more in agreement. Question order was counterbalanced and therefore it would be expected that these scores would be opposite to one another, however this result is not as clear cut. It is possible that question 5 may have led participants to consider this option and by thinking about it be more likely to answer yes.

Question 7 was included to record any unusual sensations created by viewing a hand that would differ compared to the normal somatosensory representation. Results suggest no unusual sensations were experienced on average. It was expected that some tingling in the invisible digit or discomfort in the hand may be experienced. Upon inspection of individual answers there is a lot of variation between participants ranging from strongly disagree to +2. However the majority of individual scored this question 0 suggesting they neither agreed nor disagreed.

The final two questions also support the results of the pre-stroke questions in that participants felt ownership over the virtual yellow hand despite having one less digit than they are accustomed to. Additionally ownership scores were on average higher than pre-stroke suggesting the adaptation did likely aid in increasing feelings of ownership.

## Discussion

The results of this study showed a main effect of target distance with near targets being responded to significantly faster than far targets. The absence of a significant interaction however shows that the NHE did not change as a result of changes in hand fidelity. Therefore this result first shows that an NHE can be maintained in a virtual setting, even for a hand with a missing finger. Second, it offers further insight in to the role of appearance and acceptance into the representation of the body.

Ma and Hommel (2015) previously highlighted the division in the literature between those that support the role of bottom-up factors in perceptions of ownership, and those that favour a top-down approach. They cited problems in varying methodology for the conflicting outcomes, in particular the role of visuo-tactile versus visuo-motor influences. Visuo-motor feedback has been shown to be significantly more instrumental in creating perceptions of ownership than visuo-tactile, commonly used in the RHI (Kokkinara & Slater, 2014). In the present study participants were likely able to gain a sense of agency over the limb as upon placing their hand inside the MIRAGE they were immediately able to view the hand as they moved it into position (in the form of fidelity assigned for each block). This addition of visuo-motor control that is lacking in previous research investigating fidelity may be a significant reason why the results showed less of a detriment caused by changes in appearance.

In particular our results conflict with the study by Tsakiris et al (2010) in which only the most realistic hand condition (yet still rubber) maintained a sense of ownership. It was concluded that an item had to strongly resemble a hand to be incorporated in to the body. The results found here may not directly contradict these findings though, as the present study was measuring changes in the way the space around the hand was processed, not directly a sense of ownership. However the results of the 4DIGIT hand questionnaire do offer some disagreement due to the implausible hand being scored positively for ownership ratings. It could

be argued that these differences in results are due to two factors, first the additional aspect of changes in spatial location between the visual and tactile stimulation in the study by Tsakiris, and second the visuo-motor response of the augmented hand in the present study.

With the use of the MIRAGE it was possible to manipulate the appearance of the hand and transform it into less realistic iterations of itself while the real hand remained in the same location. This meant that it was not only possible to just test the visual component without the confound of spatial location, but also that it was not possible to measure ownership changes in the same way as previous research due to a lack of proprioceptive drift being possible. This may explain why in this study no changes across appearance conditions were shown, yet in the study by Tsakiris et al. (2010) hand fidelity appeared critical to perceived ownership.

The NHE measure is not the same as an explicit ownership questionnaire, nor perceived hand location. This is partly due to the fact that an NHE should also be created on the basis of proprioceptive input regardless of visual information. However, since the NHE is not created when viewing an arbitrary visual anchor such as a block, the fidelity of the hand may have an impact on the strength of the NHE created. One potential reason for this is that if the item does not resemble a hand then a perception of ownership can not be felt, and it may be this perception that shifts the receptive fields of bimodal neurons towards the visual hand. Of course with the real hand in the same position these neurons should already be responding to targets around the hand, however previous literature has highlighted that they respond more strongly when the hand is visible (Graziano et al., 1999). Additionally, vision of the hand has been shown to improve tactile sensitivity and modulate tactile receptive fields (Haggard, Christakou, & Serino, 2007; Rorden, Heutink, Greenfield, & Robertson, 1999). Therefore it could be argued that the appearance of the hand does affect perceived ownership and the less convincing the hand is, the less likely it is that bimodal neurons will process the space around the hand as strongly as they would normally, or be as inclined to update limb

position to this location. This is why it was expected that changes in hand fidelity might alter the NHE.

One explanation for why changes were not observed could be that changes in appearance were not enough to disrupt perceived ownership over the hand. If ownership is maintained then this in turn could result in the hand processing peri-personal space consistently. The result may be different if there was another visual hand present that was not manipulated and more strongly resembled the participant's hand. The presence of a more realistic hand could cause a shift in the receptive fields of bimodal neurons in an attempt to prepare that visual hand for action, over the less realistic one. Alternatively this could highlight whether only the more realistic limb would be incorporated in to the body schema, if an NHE was still created for both hands this could highlight that body image is critical for an NHE, not the body schema, or vice versa. A future study could investigate this to bridge the gap between the current study and previous research utilising RHI methodologies in which there is a spatial separation in addition to a visual change.

Along these lines, it would also be useful to test this paradigm with the real hand removed while visually the hands remained. This would eliminate the advantage of visuo-motor feedback and would be possible using the MIRAGE. However despite removing the conflict of the proprioceptive contribution this set up would create a new issue. With their hands on their laps participants may become immediately less convinced that the visual hand is anything to do with their body and therefore changes in the appearance are not the only aspect effecting perceived ownership. It is likely that in the absence of veridical proprioceptive information changes in appearance of the hand would have a stronger influence on the NHE and would perhaps show a significant reduction for a less plausible hand such as the 4-digit condition. It may be possible to conduct a similar study in which there is only a small spatial separation, comparable to the distances observed in most RHI studies. This could be done with either a live or static image to allow or prohibit visuo-motor feedback, respectively. The contribution of visuo-

motor feedback could then be more thoroughly evaluated, with expected improvements in ownership when that feedback is available.

On reflection, it may also be worth testing the NHE on the 4DIGIT hand both before and after stroking of the hand. This would highlight if there were any changes in ownership created through synchronous visual-tactile feedback or whether the hand was embodied almost immediately due to visuo-motor contributions.

The present results may contradict some top-down theories on the basis that a hand with a missing finger showed no changes in the processing of space around it, however these results may also not fully support bottom-up theories either. The study by Armel and Ramachandran (2003) in which they demonstrated that perceptions of ownership could be created from synchronous visuo-tactile stimulation of a table and the real hidden hand have not been successfully replicated. It could be argued that the present study does not offer evidence to support the notion that anything can be embodied, despite finding no changes for reductions in fidelity of the hand. This is because each appearance condition did in some way still resemble a hand. The condition least like a hand was when the fingers were placed together and the surface detail was removed, meaning that individual digits were not visible. However the size and shape would still resemble a hand as participants were aware that they had their fingers placed together, in other words, the position of their hand did match what they were seeing, other than the lack of detail. Furthermore even in the 4-digit hand condition the absence of one finger may have conflicted with the cortical representation, but in general it was still hand like. Therefore the results from this study should not be generalised to suggest that anything can be successfully embodied as non-corporeal objects were not included.

Previous evidence that illustrated changes in ownership for non-corporeal objects have suggested it might be possible but critically seem to require a visuo-motor aspect (Ma & Hommel, 2015). However even if a non-corporeal object was perceived as being part of one's body it may still not

show a reliable NHE. If the paradigm used by Ma and Hommel (2015) was replicated, in which they controlled an object that they viewed on a vertically positioned screen in front of them while their hands were hidden from view in front of the screen, but with the addition of targets appearing near and far from the controllable object an NHE would likely not exist despite perceptions of ownership. This is suggested because resemblance to the hand is likely vital in shifting receptive fields to the location of the visual hand if the real hand is in a different location, and an NHE has not been shown to work with a hand sized block or something arbitrary (see Chapter 2 and Reed et al, 2006).

Perani (2001) showed that viewing a fake limb created different neural activation than viewing the real limb. This would suggest that changes in fidelity in our experiment may invoke different neural networks compared to BASE. Perhaps the lack of a spatial separation between the visual hand and the real hand impaired the ability of the brain to identify a fake limb. It may recognise the hand not to appear as it should, but the added influence of agency and location of limb may have overridden any decision to perceive it as a fake. If it were possible to measure neural activity whilst completing the task in MIRAGE the same levels of activity might be seen for all hand conditions including viewing the hand out of MIRAGE. It may be that it was not the vision of a fake limb that changed the activation, but the incongruence between visual and spatial limb information.

The results of this experiment have shown that changes to the appearance of the hand by reducing fidelity do not significantly alter how the space around the hand is processed. Of course this may be partly due to the veridical proprioceptive input which is sufficient to create an NHE without a visual contribution, however this should be less reliable than when congruent visual information is available, as observed by Reed et al (2006). Furthermore, if the m-cell hypothesis is solely responsible for the NHE then a less realistic 'hand' may be less primed for action and therefore fidelity should influence its strength. The high ownership ratings for a hand with only 4 digits and therefore incongruent with cortical



representations suggests that visual information about the hand may not be the most vital sensory input in acceptance of a body part. Visuo-motor information may be a more important contribution and override visual information, particularly when spatial information regarding hand location coincides with the visuo-motor input. This could suggest support for bottom-up theories of ownership by illustrating that visual information can be ignored or compensated for if other multimodal sensory information suggests the virtual object belongs to them. Future research should focus on breaking down these inputs further by testing both static and moving versions and paradigms where the visual change to the hand is separated from the proprioceptive hand. These investigations will help further evaluate why the present study produced conflicting results with previous research. In summary the present study demonstrates that reductions in fidelity of a virtual hand do not change the processing of peri-personal space around the hand.

## Chapter 6 The Effects of Temporal Lag on Motor Control and the Processing of Peri-personal Space.

The present experiment aimed to investigate to what extent a temporal delay on movement in a virtual environment impacted upon performance, and also any changes in body ownership relating to the virtual limb. As previously discussed in chapter 1, temporal lag is a continuing challenge to virtual and augmented reality systems with ever increasing demand for systems to be as realistic and complex as possible.

Temporal lag, or latency, creates a physical separation between real movements and visual feedback of those movements. Lag in various interactive systems persists as a problem, in touch screen devices (Jota, Ng, Dietz, & Wigdor, 2013), gaming (van Krevelen & Poelman, 2010), and VR training such as Head Mounted Displays (HMD's) (Azuma, 1997; van Krevelen & Poelman, 2010). These platforms vary in how the user interacts with them, and therefore lag in these contexts creates slightly different issues. For touch screen devices, moving an object around the screen can make any latency obvious to the user (Ng, Lepinski, Wigdor, Sanders, & Dietz, 2012). However in a more immersive environment, such as VR gaming, cyber or simulator sickness is a more prevalent issue (Lugrin et al., 2013). Often fidelity is prioritised at the cost of higher frame rates. This is a particular issue in HMD's where the visual scene may appear to 'swim' if head movement and scene movement are separated by a high enough lag resulting in an unstable image. (Moss, Muth, Tyrrell, & Stephens, 2010; Rolland & Fuchs, 2000).

Therefore latency can affect the overall experience for the user, but more importantly how does it affect performance? For interactive systems where a 1-to-1 sensory correspondence is vital for effective training or transfer of skills learnt in a virtual environment, can latency be detectable yet not problematic? In situations where the user is controlling an avatar, or a virtual hand, sensory correspondence should be a priority. To investigate performance issues So and Chung (2005) had participants

perform a reaching and tapping task in a virtual environment through use of a cyberglove. They performed this with added latencies of 55, 110, 220 and 440ms. Targets varied in size and distance with results showing a significant interaction between latency and target width. In other words the results suggested that movement times depended on target width as well as lag, potentially because smaller targets increase task difficulty, and this could be specific to hand movements. They also showed a significant increase in movement times with higher latencies. However the virtual environment they were using had a baseline latency of 63ms and therefore any comparisons to other literature should correct for this.

In the study by Ware and Balakrishnan (1994) in which participants moved a cursor to a target location, head and hand tracking systems with added lags were compared. They concluded that lag affecting the hand was much more important in predicting performance than lag in the head tracking system. However, lag in HMDs has still been shown to negatively impact upon performance with Nelson, Roe, Bolia and Morley (2000) showing that participants struggled to visually track a virtual object with latencies of 50-100ms in a HMD. These studies highlight that if lag affects performance in different ways depending on what the task requires (hand use or visually scanning an environment) then determining if lag is a critical problem will depend on how a user is interacting with a VR system. This may help prioritise where latencies should be reduced perhaps at the cost of fidelity.

Other research has highlighted different points at which temporal lag significantly affects performance across various types of task. 2D mouse to target tasks have shown that visual lags of 69ms (Jay & Hubbard, 2005), 50ms and 110ms (Pavlovych & Gutwin, 2012), and 225ms, (MacKenzie & Ware, 1993) to be the points at which performance significantly declines. However, interacting with a 1D or 2D display requires the user to adapt to a novel visuo-motor set-up (Viciano-Abad, Reyes-Lecuona, Poyade, & Escolano, 2011). Considering today's VR systems are more developed than a 2D interface these results may not be as relevant as experiments employing 3D or more immersive virtual environments.

In more modern VR settings users are able to go further than just viewing an environment but can actually take control of a virtual body, or part of a virtual body such as an arm. Much of this research has focused on the importance of sensory integration and how well a person is able to 'embody' the virtual effector. One such study involved participants receiving tactile stimulation to their real arm synchronously with visual stimulation to a virtual arm, which appeared to project out of their shoulder with the aid of stereo glasses and a head tracker. Questionnaire responses suggested that ownership was displaced towards the virtual arm, but not with asynchronous stimulation (Slater et al., 2008). A similar study investigated the effects of embodiment over a virtual hand without providing any form of tactile-visual synchronous feedback. Instead participants had to imagine a motor movement and then viewed the virtual hand making a movement. They reported that participants successfully transferred ownership to the virtual arm simply through these motor imagery tasks, however proprioceptive drift was not reported as successful (Perez-Marcos, Slater, & Sanchez-Vives, 2009). Interestingly they also reported muscle activity in the real arm when viewing spontaneous movement of the virtual limb. These studies suggest the embodiment of a virtual limb is possible, but asynchronous visual-tactile sensory feedback can disrupt this process.

It has been suggested that interoception (the sense of the body from the inside) plays a role in the underlying mechanism of body ownership of a new effector. One study demonstrated that both subjective and objective measures of ownership were influenced by cardio-visual feedback (Suzuki, Garfinkel, Critchley, & Seth, 2013). They showed that synchronous pulsing of the virtual hand (with their heartbeat) enhanced ratings of ownership and suggested that synchrony in terms of interoception was important in accepting something as part of the body.

A further study that investigated the effect of temporal lag on hand movements in relation to ownership and agency suggested that lag affects these two concepts in different ways (Imaizumi & Asai, 2015). They asked participants to clasp and unclasp their hands together while viewing the

hands on a monitor that had added delays to the image. Their results indicated that while agency was able to recalibrate over time, ownership as measured by proprioceptive drift did not. As a result, they argued that temporal incongruence affected agency and ownership in different ways. However due to the visual hands not being spatially synchronous with the real hands results may be confounded. Another virtual hand illusion study looked at functional imaging data when asynchronous stroking of the hands was delayed by either 300 or 600ms (Bekrater-Bodmann et al., 2014). They found that asynchronies of 600ms lowered the vividness of the illusion, while 300ms did not. They concluded that they had demonstrated temporal limits to the induction of ownership.

The evidence presented so far tells us that temporal lag in virtual settings hinders performance, but this has mainly been investigated in now outdated paradigms due to the rapid improvements in VR development, or scenarios in which other variables such as spatial location could be confounding results. The current study aimed to investigate the effect of lag using the MIRAGE mediated reality system (see chapter 2) without the confounding factors of arm position or the embodiment of fake limbs that do not resemble each participant's limb. In other words, what is the pure effect of temporal perturbations on movement and does lag change the perception of a virtual arm and the processing of peri-personal space?

Previous studies using the MIRAGE have shown that participants scored highly on having a sense of ownership over the virtual hand, even when the hand is not in its veridical location but synchronous visual tactile feedback is given (Newport et al., 2010). Their study also demonstrated that when presented with two identical virtual hands, one in the veridical location, no sense of ownership was reported for the temporally asynchronous hand suggesting that a temporal perturbation is more detrimental than a spatial separation in terms of ownership. Through the use of the MIRAGE the present study is perhaps the first that is able to investigate the effects of lag on movement with limbs in a spatially correct location that would apply to relevant VR/AR systems such as Oculus Rift.

To do this, a simple reach to target task was designed to be run within the MIRAGE workspace in which participants would view a virtual representation of their own hand. Across 4 conditions participants experienced additions of temporal lag in 75ms increments, starting at 0ms added to allow a baseline comparison. These relatively large increments were chosen to cover the range of suggestions from the literature for the point at which lag critically effects performance. Whilst making reaching movements to targets that appeared pseudo-randomly within the workspace participants were equipped with a motion sensor that recorded a variety of kinematic measures. It has previously been demonstrated that individuals make the same types of movements and exhibit similar kinematics in a VR setting as they do in the real world (Dvorkin, Shahar, & Weiss, 2006). This should allow results to be transferable from VR settings to AR environments as well. The first stage of the experiment was a practise as a control stage, allowing participant's time to adapt to the lags, while 'LAG' refers to the main reaching stage (performed immediately after with the same amount of lag) consisted of new target locations and was the primary stage of interest. By LAG it was expected that movements to targets would be more consistent across trials.

After each movement task participants would perform a simple reaction time task to assess any changes to the NHE. With mixed evidence in the literature suggesting both no adaption of ownership (Imaizumi & Asai, 2015), and temporal limits needed to disrupt ownership (Bekrater-Bodmann et al., 2014) it remains unclear whether temporal lag could disrupt the body representation and in turn impact upon the processing of peri-personal space.

It was hypothesised that, in line with previous research, (In & Seungmoon, 2007; Jay & Hubbard, 2005; MacKenzie & Ware, 1993), performance in terms of accuracy and movement times would become impaired as temporal lag increased. Therefore each added lag condition would be statistically compared to the 0ms condition. Additionally due to the increase in incongruence between visual and proprioceptive feedback, ownership (Slater et al., 2008), agency (Perez-Marcos et al., 2009), and

presence (Viciano-Abad et al., 2011) would decrease. This would be assessed through questionnaire measures. An NHE task, as employed in previous chapters, would also assess any changes in the processing of peripersonal space as lag was increased and was presented after the reaching components of the task.

## Methods

### Design

The experiment employed a 2 x 4 repeated measures design with Target Distance (2 levels; near ~2cm, or far ~15cm from the hand) and Temporal Perturbation (4 levels; baseline, 75ms, 150ms and 225ms) as the independent variables. This was the amount of temporal lag added to the MIRAGE system. Baseline refers to no lag added, however the MIRAGE itself has a lag of 10ms. Therefore technically the conditions could be referred to as 10ms, 85ms, 160ms and 235ms. The dependent variable was reaction time to target as recorded by foot pedal response.

In addition to the NHE measure, a variety of kinematic measures were recorded during the reaching movements to targets for each temporal perturbation. Measures include movements time (MT), Peak Velocity (PV), percentage of time in the deceleration phase (%DP), angle error, distance error, and total error.

Third, questionnaires were issued to participants relating to how they felt about the virtual hand, including measures of ownership, agency, presence, size and weight changes, and unusual sensations.

### Participants

A total of 24 participants were recruited through recruitment posters placed around the University of Nottingham and through the University's online research participation scheme, SONA. Participants were aged 20-28 ( $M=20.87$ ,  $SD=1.76$ ), 20 were female. An inconvenience allowance of £7/hr was given. All gave informed consent and understood they could withdraw at any time.

### Polhemus Liberty Motion Tracker

A Polhemus Liberty Motion Tracker was used to record hand movements accurately within the MIRAGE. Participants wore a sensor strapped to their index finger which tracked their movements within the MIRAGE workspace. Kinematic data (in the form of x,y, and z co-ordinates) such as hand path and velocity profiles were collected and stored on the computer. When used in conjunction with the MIRAGE Polhemus



sampled at 150Hz with a resolution <1mm. Data were collected using this method, in which participant's made reaching movements to targets, prior to the NHE stage (NHES) of the experiment. At the start of each testing session calibration trials were performed for each target location and to ensure the sensor was recording correctly.

### Stimuli

Targets were displayed within the MIRAGE workspace digitally as red circles with a diameter of 12mm for Practise and LAG, and 7.92mm in diameter for NHES reaction time targets. Targets were displayed in two rows on the far side of the workspace for the practise and a diamond shape for LAG (see Figure 6-1 and Figure 6-2).

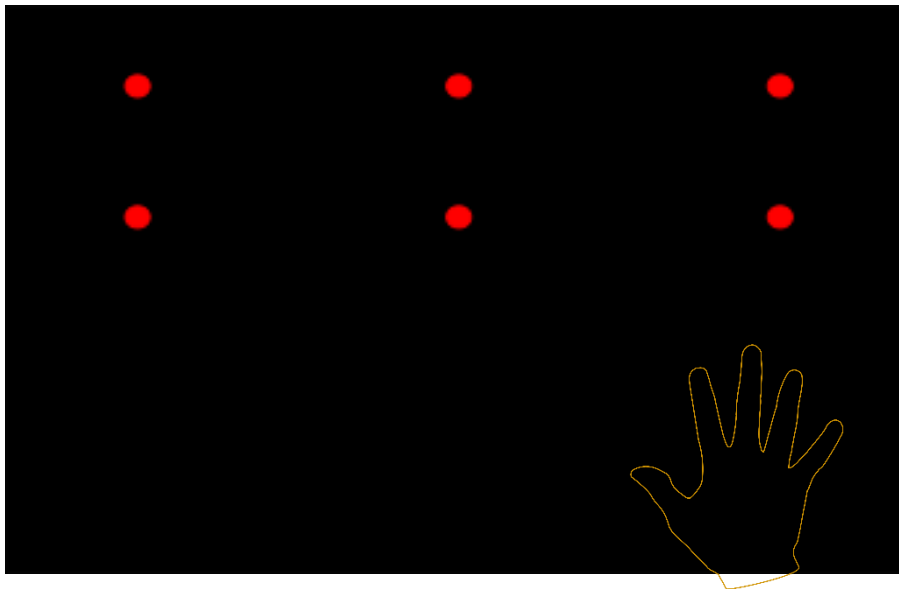


Figure 6-1: Representation of the MIRAGE workspace showing targets in the 6 possible practise locations. Hand represents starting position of hand for each movement.

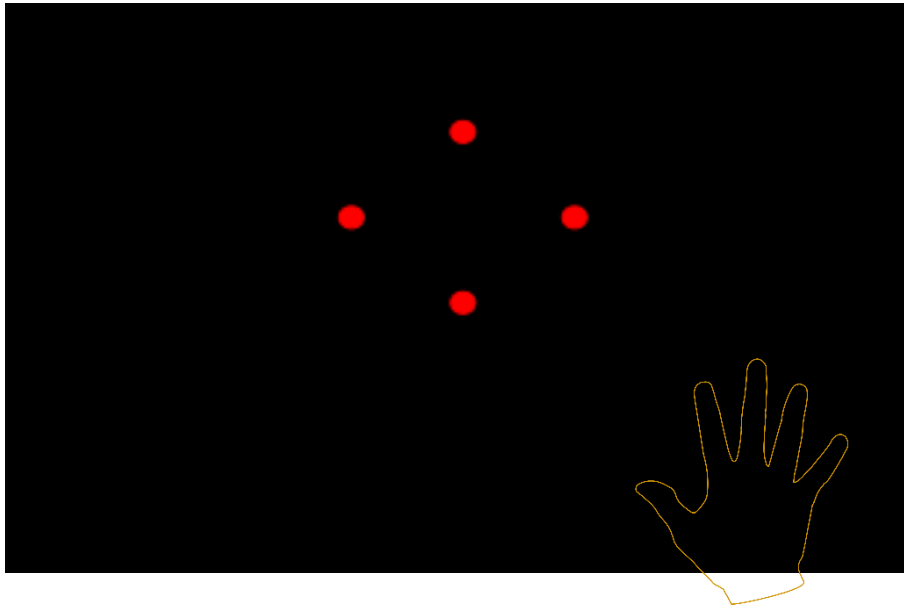


Figure 6-2: Representation of the main stage targets in their 4 possible locations within the MIRAGE workspace. Targets appeared one at a time.

### Questionnaire

A questionnaire was designed in order to assess levels of ownership, agency, presence, size and shape changes, and any unusual sensations over the virtual hand (see Table 1 in chapter 3 or appendix 2). Example questions include ‘The hand I saw felt like it was part of my body’ and ‘The hand I saw belonged to me’. This measure adapted questions from established questionnaires used to assess the rubber hand illusion (Botvinick & Cohen, 1998) and was adapted for MIRAGE (Newport & Preston, 2011). 13 questions were verbally administered, 3 were on ownership, 3 on agency, 2 on presence, 3 regarding size and weight changes, and 2 on unusual sensations. Participants were asked to respond using a numerical scale ranging from -3 for strongly disagree, to +3 for strongly agree. 0 was a valid score indicating participants neither agreed nor disagreed.

### Procedure

Upon completion of the consent forms participants were fitted with the motion tracker sensor. This was secured to the tip of the index finger using hypoallergenic tape in addition to being fed through a bandage on the wrist to ensure the cable was secure.

Participants were instructed to place their hand inside the MIRAGE with their wrist placed on a tactile marker. This marker represented where they should return their hand to between each target appearance to ensure the starting position for each reach was consistent.

The task had 3 stages. Practise (Stage 1) involved participants reaching to targets in 6 possible locations across the MIRAGE workspace, with each target appearing 5 times (Figure 6-1). LAG (Stage 2) presented participants with 4 new target locations, with each target appearing 10 times (Figure 6-2). Participants completed the task by reaching towards the targets as they appeared one at a time, pseudo-randomly, and placed their index finger on the surface before retracting their hand back to the starting position. Targets were displayed for 2 seconds and disappeared on contact with the hand. They were asked to make this movement as quickly and accurately as possible. Additional lag was added for both the practise stage and LAG, either 0, 75, 150, or 225ms.

The purpose of the practise stage was to give participants time to adapt to the lag and compensate for any initial difficulties that may have skewed results. By LAG any initial confounds with being presented with a new sensorimotor environment should have been overcome. New locations were presented so that participants were not reliant on motor memory and still made use of the visual and proprioceptive information.

The questionnaire was administered verbally by the experimenter after the practise, asking participants to reflect on how their hand felt during the perturbation. The questionnaire was employed at this point, rather than after LAG, in order to minimise the time between the exposure of any additional lag and the start of the third stage. This was important as removing the hand at this point from MIRAGE, or seeing it with no perturbation, could stop any changes in embodiment being carried over for the NHES.

NHES was the NHE stage in which participants placed their hand stationary and responded to 80 targets appearing near or far from the hand via foot-pedal response (as in previous chapters).

Stages 1-3 were repeated 4 times with each temporal perturbation, 0, 75, 150 and 225ms, order was counterbalanced across participants. Each perturbation (stages 1-3, plus questionnaire) lasted approximately 8 minutes. After completion of all 4 perturbations participants were debriefed.

## Results

### Kinematic Data Analysis

Data were collected from 24 participants, however participants 1, 3 and 6 were removed due to errors that occurred in the recording of the kinematic data by Polhemus. Each participant generated a total of 280 data files, 70 per temporal condition.

The practise stage was not analysed as it acted as a control to ensure data was not skewed while participants were adapting to any additional lag. The following analyses refer to LAG. All analyses were conducted using repeated measures ANOVA's to look for any changes across temporal conditions. It was predicted that increases in delay would increase movement times, amount of distance error, and percentage of time in the deceleration phase compared to 0ms.

Movement Time violated the assumption of sphericity,  $X^2(5) = 19.12$ ,  $p = .002$ , therefore the Greenhouse-Geisser correction was used ( $\epsilon=.64$ ). This resulted in a significant main effect of temporal perturbation,  $F(1.93, 36.73) = 4.66$ ,  $p = .017$ ,  $\eta_p^2 = .20$ . Simple contrasts comparing each average Movement Time to 0ms baseline condition revealed significant differences for 75ms ( $p=.03$ ) and 225ms ( $p=.001$ ), but not for 150ms ( $p=.12$ ), most likely due to the amount of variation across scores for this condition. (Figure 6-3).

Peak Velocity shows the maximum speed participants reached in making their movements to targets, and could indicate task difficulty. Sphericity was violated ( $X^2(5) = 17.54$ ,  $p = .004$ ) the Greenhouse-Geisser correction was applied ( $\epsilon=.61$ ),  $F(1.82, 34.65) = .55$ ,  $p = .57$ ,  $\eta_p^2 = .03$  showing no changes across perturbations.

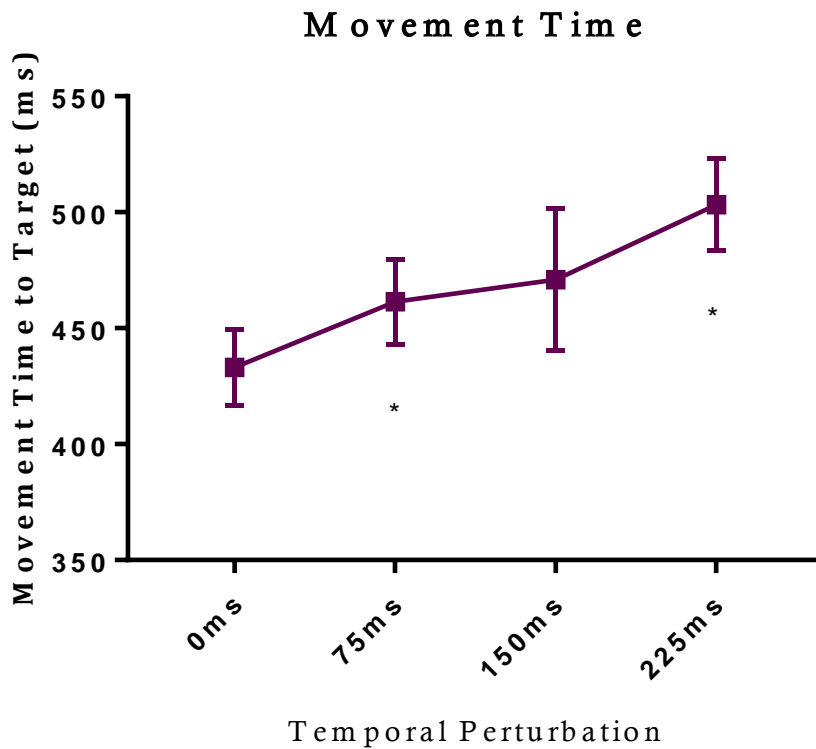


Figure 6-3: Significant differences were found between 0ms and both 75 and 225ms, but not for 150ms.

Percentage of time in the Deceleration Phase (%DP) is an indication of task difficulty, with a longer time spent in this phase suggesting participants are focusing harder on being accurate by taking longer to slow down. Results showed a significant main effect,  $F(3,57) = 3.69$ ,  $p = .02$ ,  $\eta_p^2 = .16$  with simple contrasts highlighting the differences to be significant at 150ms ( $p = .03$ ), and 225ms ( $p = .04$ ). See Figure 6-4.

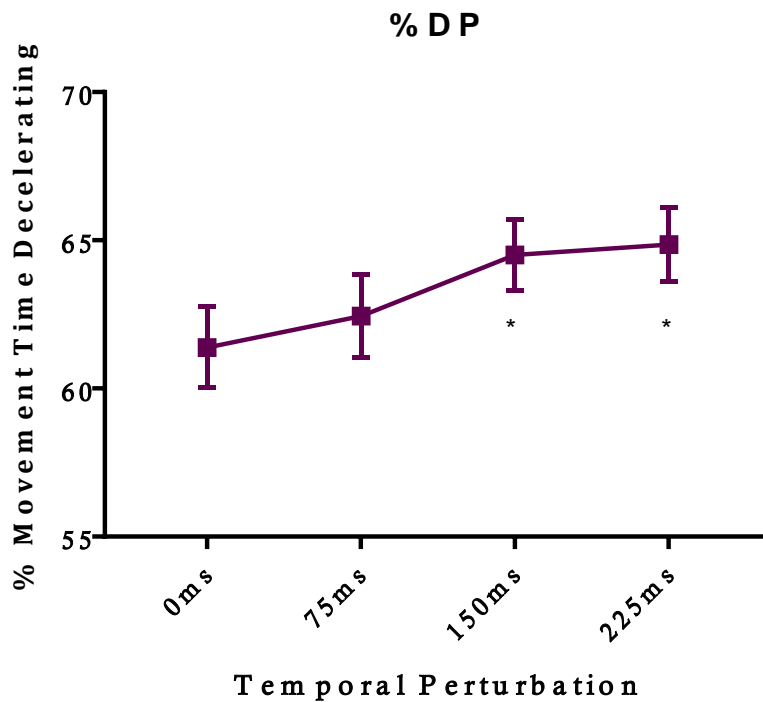


Figure 6-4: Significant changes were observed between 0ms and 150ms, and 0ms and 225ms. Indicating increased task difficulty at these perturbations.

Distance Error violated the assumption of sphericity, ( $X^2(5) = 24.41$ ,  $p < .001$ ) and therefore the Greenhouse-Geisser correction was used ( $\epsilon = .54$ ). This resulted in a significant main effect being found,  $F(1.62, 30.79) = 11.53$ ,  $p < .001$ ,  $\eta_p^2 = .38$ . Simple contrasts showed these differences to be for 75ms ( $p = .02$ ), 150ms ( $p < .001$ ), and 225ms ( $p = .002$ ). (Figure 6-5).

Angle Error represents how accurate participants were at hitting the targets. The assumption of sphericity was violated, ( $X^2(5) = 18.57$ ,  $p = .002$ ), and therefore a Greenhouse-Geisser correction was applied ( $\epsilon = .62$ ). However, the results were non-significant  $F(1.86, 35.31) = 1.30$ ,  $p = .29$ ,  $\eta_p^2 = .06$ .

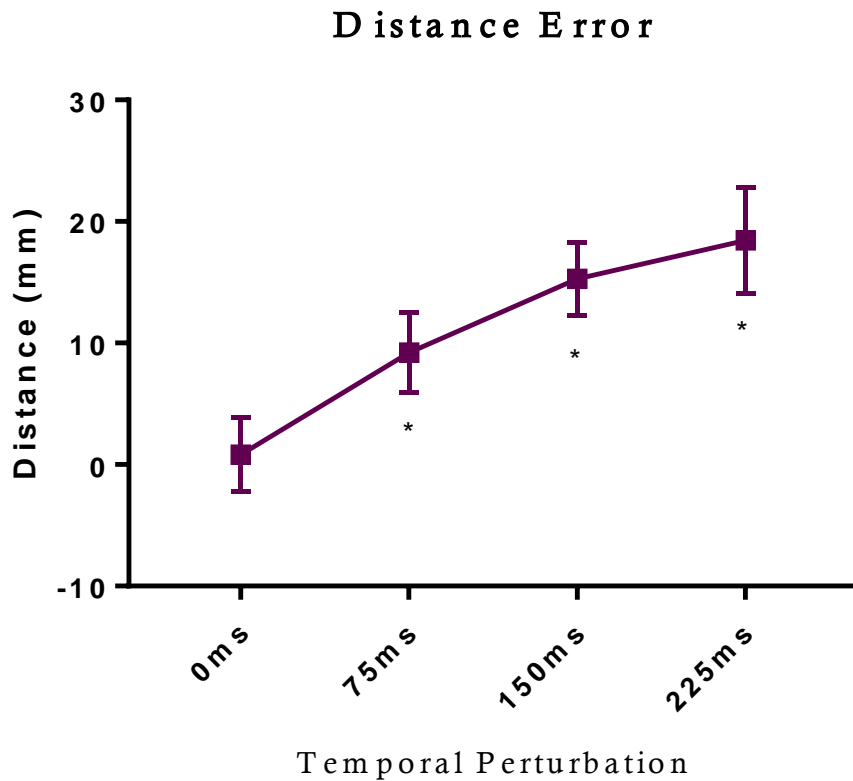


Figure 6-5: As lag increases significant increases in distance error are shown for all conditions compared to 0ms added.

Total Error refers to how accurate participants were overall, combining angle and distance information to give one measure of error. Results of the ANOVA revealed a significant main effect,  $F(3,57) = 8.69$ ,  $p < .001$ ,  $\eta_p^2 = .31$ . Simple contrasts revealed significant differences at 150 ( $p = .003$ ) and 225ms ( $p = .001$ ). See Figure 6-6.

In summary, most changes were observed from 150ms, however MT and Distance error saw changes from 75ms. No significant differences were observed for PV and Angle error.



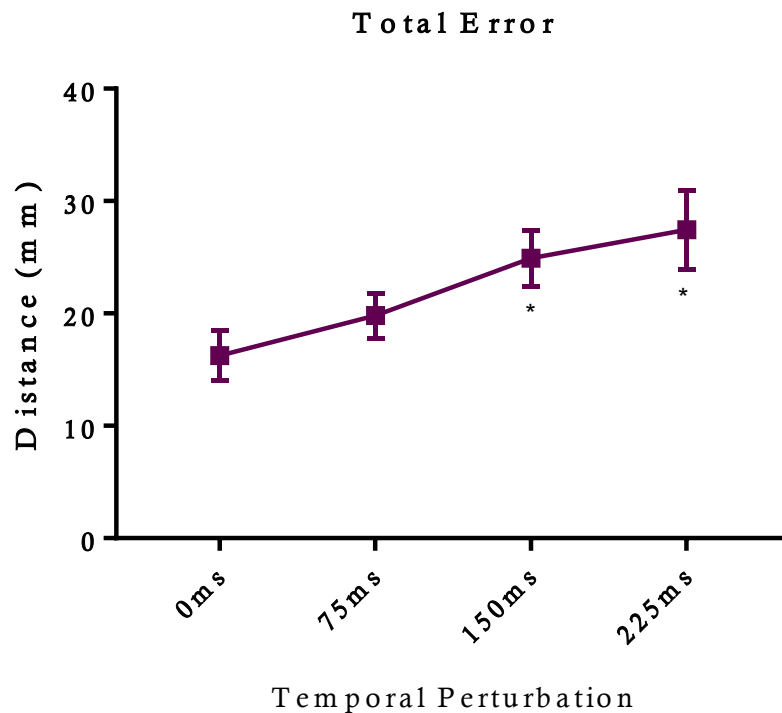


Figure 6-6: Added lag of 150 and 225ms showed significantly greater total error compared to 0ms.

### Reaction Time Data

Reaction times were recorded via foot-pedal response to targets appearing near and far from the hand for the NHE stage. As there was more variation across participants than across conditions, data were trimmed per participant using a lower cut-off of 100ms, and +2 standard deviations. The lower absolute cut-off was chosen as 100ms as this is considered the minimum amount of processing time needed to detect a stimulus and elicit a motor response (Whelan, 2008). This method was different to previous chapters. Percentage of trials excluded totalled at 6.3%, within recommended limits (Ratcliff, 1993).

Average reaction times per participants for near and far targets for each temporal condition were put into a repeated measures ANOVA to evaluate any differences across conditions. Results showed a significant main effect of target distance,  $F(1,23) = 58.94$ ,  $p < .001$ ,  $\eta_p^2 = .72$ ,

highlighting near targets ( $M=411.41$ ,  $SE=10.05$ ) were responded to significantly faster than far targets ( $M=428.48$ ,  $SE=11.28$ ) regardless of condition. However no significant main effect was observed for temporal perturbation,  $F(3,69) = .67$ ,  $p = .57$ ,  $\eta_p^2 = .03$ , showing no differences between 0ms ( $M=426.32$ ,  $SE=13.14$ ), 75ms ( $M=412.53$ ,  $SE=12.04$ ), 150ms ( $M=423.46$ ,  $SE=12.12$ ) or 225ms ( $M=417.48$ ,  $SE=12.54$ ). Additionally no significant interaction was found,  $F(3, 69) = .646$ ,  $p = .5$ ,  $\eta_p^2 = .03$  suggesting that the difference between near and far targets was not dependent on the amount of temporal lag added (Figure 6-7).

Simple Main Effects analysis showed that at each level of temporal perturbation the difference between near and far reaction times was significant.

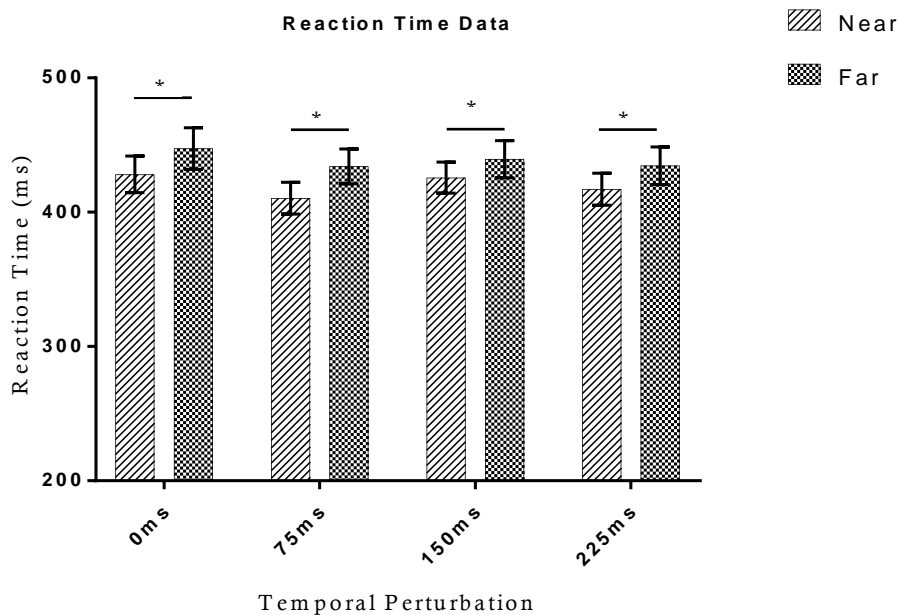


Figure 6-7: Graph showing reaction times to near and far targets during NHES of the task. X axis shows different perturbations. Asterisks represent significant differences between near and far conditions.

## Questionnaire Data

The questionnaire was scored on a scale of -3 for strongly disagree to +3 for strongly agree. 0 was a valid score implying the participant neither disagreed nor agreed. The following questions were inversely scored, 'it seemed as if I had more than one right hand', 'it seemed as if the virtual hand had a will of its own' and 'the computer was controlling the hand I saw'. These questions were from the ownership, agency, and presence categories respectively and acted as controls for the other questions within each category. All questions regarding 'sensations' and 'size & weight' were expected to be negatively scored as they reported any changes in size and weight, or unusual sensations experienced, e.g. 'I felt an ache or throbbing in my hand'. Figure 6-8 illustrates averaged questionnaire scores across all participants, showing each temporal perturbation condition.

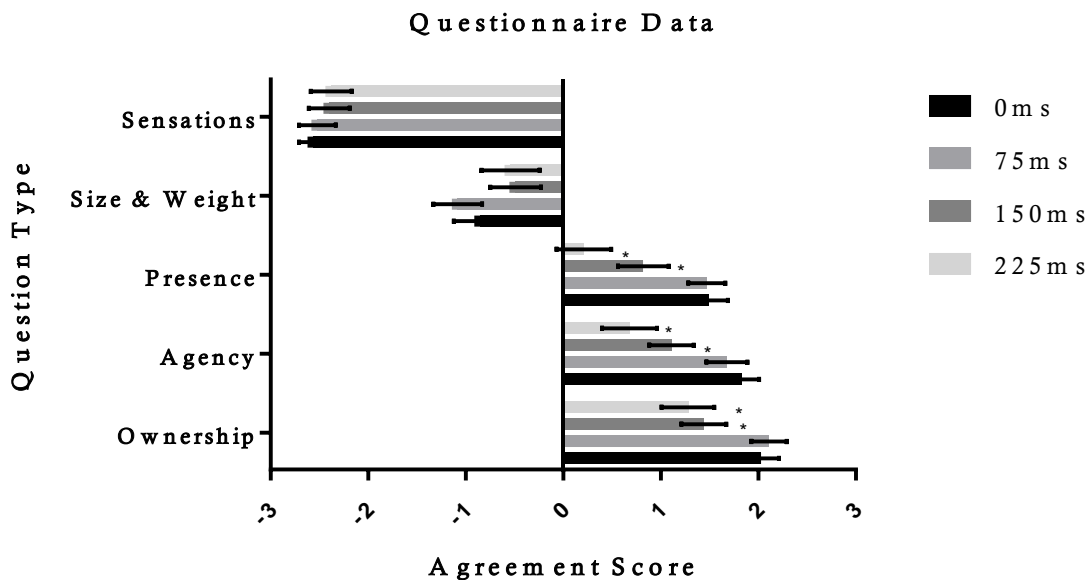


Figure 6-8: Questionnaire scores taken after each temporal perturbation relating to how they felt about the virtual hand. Positive scores indicate agreement while negative values demonstrate disagreement with each question. A score of 0 indicates that participants. Asterisks indicate significant changes compared to 0ms condition within each question type.

A repeated measures ANOVA was conducted comparing ownership scores across each temporal perturbation condition, with sphericity assumed, ( $X^2(5) = 10.92, p = .053$ ), and showed a significant main effect,  $F(3,69) = 80.94, p < .001, \eta_p^2 = .78$ . Planned contrasts comparing each perturbation to 0ms showed the differences to lie between 0ms and 150ms,  $p = .001$ , and 0ms and 225ms,  $p < .001$ .

Agency scores were also analysed using a repeated measures ANOVA and showed a violation of sphericity,  $X^2(5) = 13.35, p = .02$ , therefore by referring to the epsilon values a Huynh-Feldt correction will be referred to as  $\epsilon > .75$  ( $\epsilon = .79$ ). This showed a significant main effect of temporal perturbation on agency scores,  $F(2.38, 54.62) = 12.37, p < .001, \eta_p^2 = .35$ . Planned contrasts showed no significant difference between 0ms and 75ms,  $p = .38$ , but did show significant differences between 0ms and 150ms,  $p < .001$ , and 0ms and 225ms,  $p < .001$ . These results highlight significant changes in perceived ownership and agency for 150ms and 225ms compared to no added temporal perturbation.

The results of the repeated measures ANOVA for presence scores with sphericity assumed ( $p = .35$ ) showed a significant main effect of temporal perturbation,  $F(3,69) = 10.70, p < .001, \eta_p^2 = .32$ . Planned contrasts again showed the key differences to be between 0ms and 150ms,  $p = .01$ , and 0ms and 225ms,  $p < .001$ .

Results for perceived changes in size and weight of the hand showed a violation of sphericity,  $X^2(5) = 15.56, p = .008, \epsilon = .82$  giving a Huynh-Feldt correction showing a significant main effect  $F(2.46, 56.56) = 3.67, p = .02, \eta_p^2 = .14$ . However contrasts showed that any significant differences were not between 0ms and any other condition meaning the differences were likely between 75ms and 150ms based on the means. Based on what was predicted we can conclude that temporal perturbation did not significantly alter perceived presence as compared to 0ms baseline condition.

However, this result was achieved without inverting one of the measures in order to give an overall estimate of any possible changes, whether the hand was bigger or smaller without expecting one to be more likely. This could have nullified a result if the hand did feel heavier due to the same scoring being used to answer 'my hand felt lighter than usual'. Therefore to fully investigate whether there was a directional effect of perceived weight the analysis was recalculated with scores being inverted for the above question. This did change the results,  $F(3,69) = 6.36$ ,  $p = .001$ ,  $\eta_p^2 = .28$ , with significant differences being shown to be between 0ms and 225ms,  $p = .008$ , suggesting participants felt their hand was heavier with 225ms lag than in the 0ms condition.. See Figure 6-9 for the updated representation of results. Due to inverting one of the questions, if participants felt no change towards their hand, then we would now expect a rating closer to 0 for the 0ms condition. A rating towards the positive side of the scale, such as that now seen in the 225ms condition, indicates participants were more likely to say that their hand felt heavier than usual (or be more certain that their hand was not lighter than usual). However scores are still less than 1 indicating participants neither agreed nor disagreed.

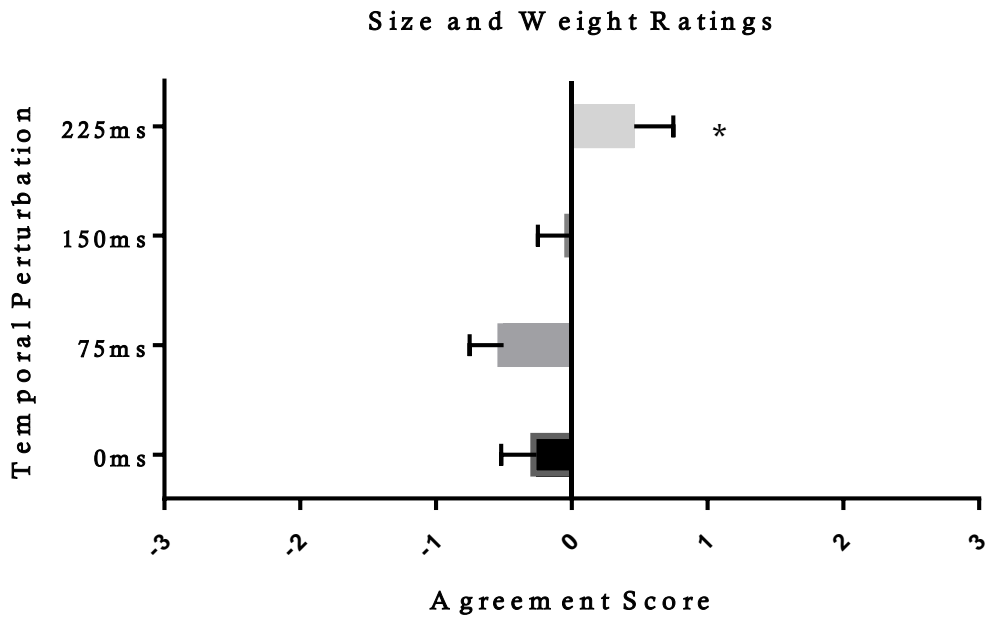


Figure 6-9: Size & weight scores with 'lighter' question inversed showing for 225ms hand is closer to being perceived as heavier than usual.

Ratings for perceiving any unusual sensations during the temporal perturbations did not show any significant changes,  $F(3,69) = .70, p = .56, \eta_p^2 = .03$  with scores indicating that participants did not experience any unusual sensations whilst viewing their virtual hand. See Table 5.

Table 5: Table containing mean (and SEM) for each averaged score across temporal conditions and question category.

Questionnaire measure	0ms	75ms	150ms	225ms
Ownership	2.03 (0.18)	2.11 (0.18)	1.44 (0.23)	1.28 (0.27)
Agency	1.83 (0.18)	1.68 (0.21)	1.11 (0.23)	0.68 (0.28)
Presence	1.49 (0.20)	1.47 (0.19)	0.82 (0.26)	0.21 (0.28)
Size & weight	-0.85 (0.27)	-1.08 (0.25)	-0.49 (0.26)	-0.54 (0.30)
Size & weight (corrected)	-0.26 (0.26)	-0.50 (0.25)	-0.01 (0.24)	0.46 (0.29)
Sensations	-2.56 (0.15)	-2.52 (0.19)	-2.40 (0.21)	-2.38 (0.21)

## Discussion

The reaction time results did show a significant difference between near and far targets, replicating previous data that a significant NHE is created within the virtual environment (see chapter 2). However no significant interaction indicates that the temporal perturbations did not influence reaction times in the NHE stage. The idea behind this was that being exposed to a temporal perturbation could change the way the virtual hand is perceived. If ownership over the virtual hand could be lost due to higher temporal perturbations then it's plausible that the visual contribution to the NHE would be less effective, relying more on proprioceptive inputs. A less reliable NHE was subsequently expected as reliance would only be on one input rather than both modalities, as observed by Reed et al. (2006).

The results of the ownership questionnaire, discussed below, do show a reduction in ownership scores with higher perturbations, yet no differences in the NHE were shown. It may be that by having the hand stationary, in order to respond to fixed target locations, any changes in ownership were restored by NHES as the incongruent visual information was no longer present. The results of the simple main effects analysis showed that the NHE was present after each temporal perturbation. This result could highlight the adaptive nature of body representation in that as soon as any sensory incongruence is removed the effected limb or body part is represented as normal again. Cardinali, Brozzoli and Farnè (2009) suggested that changes in body schema are dissociable to changes in the processing of peri-personal space, and that the cause of change in one does not necessarily create changes to other. This distinction could explain why we saw changes in the kinematic data yet no disruption to the NHE and support the notion that these two concepts are operationally separate.

The kinematic results have highlighted that movement time, distance error, percentage of time in the deceleration phase (%DP), and total error were all significantly altered by 150ms, with distance and movement time being affected from 75ms. Movement times were longer for the overall

reach, and %DP was increased in the longer latencies indicating task difficulty was increasing as participants are beginning to reduce their speed of movement sooner in order to be more accurate. Similarly longer overall movement times suggests participants found touching the target accurately more difficult and therefore reduced their speed to compensate.

This result suggest that somewhere between 75 and 150ms is enough to significantly degrade performance and is in line with some research (Pavlovych & Gutwin, 2012) but is much higher than other suggested thresholds (In & Seungmoon, 2007; Jay & Hubbard, 2005). However these disparities could be reliant on the exact nature of the task. In cases where lower thresholds were observed to impact upon performance the tasks employed were much simpler e.g. mouse to target tasks. Pavlovych and Gutwin (2012) found a lower threshold of 50ms deteriorated performance for target acquisition accuracy but a higher threshold of 110ms for object tracking. For this type of task in which the user is performing an action but seeing the result elsewhere i.e. in the form of a cursor, recruits additional processes. Perhaps our threshold is higher because the hands are congruent spatially and therefore no compensation for this is required. The present experiment examined purely the effect of lag while other sensory cues are congruent unlike previous literature in which lower thresholds have been observed. The results of this study could be more applicable to modern VR and AR systems such as HMD's in which interactions are not mouse/cursor based.

The effect of lag on an embodied effector has not been previously studied in terms of kinematic body movements. Past research investigating virtual limbs have focused on embodiment rather than performance issues and have primarily demonstrated that asynchronous visuo-proprioceptive/visuo-tactile feedback disrupts embodiment of the limb (Perez-Marcos et al., 2009; Slater et al., 2008). Despite this evidence, disembodiment may not have occurred in this experiment due to the lack of a conflicting effector. Newport et al., (2010) demonstrated a preference for perceived ownership over a temporally synchronous hand when two hands were presented, but it is not clear what would have happened had only one



hand had been presented, in the veridical location but temporally asynchronous. Would this have been enough to disown the hand completely? The results presented here could be argued to suggest that although lag may make the task harder (as seen in the %DP and MT result) it is not enough to disembodify the hand when other sensory inputs are congruent. The nature of the task may also explain the comparatively high threshold before a significant deterioration in performance.

New target locations between Practice and LAG were so that motor memory would not be a confounding factor. It was important to have the practise stage to then get a true measure of any changes in performance that were a result of the temporal perturbations rather than interacting with a novel sensorimotor environment. In a standard VR setting, people adapt to their new environment quickly, our study shows that despite this adaption time allowed by the practise, lag still creates an issue for performance at 150ms, and degradation in ownership and presence scores.

The results of the questionnaire data show, with a score close to 2, that when no lag was added participants agreed with the statements ‘The hand I saw felt like it was part of my body’ and ‘it felt as if the hand I saw belonged to me’ and inversely agreed that it did not feel like they had an extra hand (control question). This score implies that ownership over the virtual hand was achieved. Interestingly, in each temporal condition, scores on average still remained above 1 suggesting they always felt some degree of ownership, however this did decline with increased lag. The results of the ANOVA show that a perturbation of 75ms was not enough to alter perceived ownership significantly, but both 150ms and 225ms were sufficient. It is important to note that although there was a significant decline for these perturbations, there was not a total loss of ownership.

Much of the previous literature would suggest that ownership would be lost if asynchronous sensory information was provided (Perez-Marcos et al., 2009; Slater et al., 2008), and therefore it was expected that ownership over the virtual hand would decline for any perturbation. However a more

recent study has suggested that depending on the perceived strength of the illusion from other contributing factors, visuo-tactile synchrony may not be necessary for a sense of ownership to prevail (Maselli & Slater, 2013). The study highlighted that other sensory cues such as hand position and first person perspective could be sufficient to induce ownership over a virtual body, particularly noting that a high degree of overlap between the real and virtual body is a primary factor. However with no additional lag added, the authors' reasons for concluding this was due to visuo-motor synchronicity.

Similarly, agency scores were also close to 2 in the 0ms condition and saw a decline as lag was increased. As with ownership, the critical perturbation that resulted in significant changes in perceived agency was 150ms, with 225ms showing the same effect. The results of the presence questions followed the same pattern. These results suggest that 150ms is significantly detrimental to the way the virtual hand is perceived by the user. It may be that a perturbation lower than this also elicits significant results, somewhere between 75 and 150ms. This is in line with previous literature suggesting that latencies in the range of 50-90ms can lead to a reduction in presence (Meehan, Razzaque, Whitton, & Brooks, 2003).

In terms of size and weight changes, it was expected that in the 0ms condition scores would be close to -3 indicating their hand did not feel different compared to normal (in a non VR setting). However by referring to the means in Table 5 it is evident that this was not the case, with scores being close to -1 and 0. This would suggest that participants were perhaps unsure of whether their hand did feel heavier, lighter, or bigger. This measure was designed to highlight if the hand felt different to normal, however due to not inverting any of the scores for this purpose this may have resulted in one of these changes being nullified in the averaging process. Therefore a secondary analysis was performed with the scores for 'my hand felt lighter' being inverted. The results then changed to show a significant difference between 0ms and 225ms, with scores for 225ms being on the positive side of the scale indicating that some participants may have felt their hand was heavier than usual with this perturbation

added. However, the average score was less than 1 meaning that many participants may have been unsure, answering 0, or that there was a lot of variation across participants. But the significant difference does suggest that a larger lag does influence the size or weight perception of the hand.

In retrospect, a way to improve the task could be to ensure changes to the NHE are tested during the temporal perturbations rather than relying on the existence of carry over effects. However having targets appearing whilst performing a reaching task would divide attention. Or by having a task where the hand is continuously moving creates the issue of ensuring targets are a consistent distance away for 'near' and 'far'. However if there was a way to test the NHE whilst the hand was moving that would provide further insight in to the effect lag might have on the way space around the virtual effector is processed.

The results presented in this chapter highlight that a temporal discrepancy between visual and proprioceptive inputs can reduce feelings of ownership and agency, in addition to changes in movements. This has implications for VR in that performance may be affected if temporal lags in the region of 150ms exist. These results also suggest that to maintain a strong sense of ownership and agency temporal integration of visual and proprioceptive modalities must be synchronous. At least when only one effector is present: RHI literature would suggest that proprioception does not need to be congruent for ownership to be experienced, however vision and touch do. Combining this research it is likely that at least two sensory modalities need to experience synchrony in order to create the illusion of ownership and agency over a virtual effector.

In summary, in line with our hypothesis a decline in ownership scores was observed as lag increased however, no changes to the NHE were observed across temporal lag conditions implying the way we process the space around the virtual hands is not affected when the hand returns to being stationary. Despite this, motor control in the virtual environment was affected, primarily from 150ms, affecting movement times and accuracy in reaching to target, as well as making the task harder for

participants. Therefore the next experiment was designed to see if the use of non-invasive brain stimulation, namely tDCS, could be used to overcome these issues and potentially improve motor control when a 150ms perturbation exists.

## Chapter 7 The Effects of tDCS on adapting to Temporal Lag in a Virtual Environment.

Chapter 6 demonstrated the effects of disrupting visual-proprioceptive integration through temporal delay. It was shown that a lag of 150ms was the point at which performance was significantly different compared to 0ms. In conjunction with these results the questionnaire data revealed that perceptions of ownership, agency, and presence over the hand significantly declined at 150ms. The role of the posterior parietal cortex (PPC) has long been associated with the integration of visual, proprioceptive, and tactile sensory inputs (Ehrsson, Holmes, & Passingham, 2005) specifically relating to the representation of the body (Bolognini & Maravita, 2007; Giummarra et al., 2008) and the processing of peri-personal space (Iriki et al., 1996; Lloyd, 2007). The PPC has also been shown to be active in tasks where there is asynchrony between vision and proprioception during limb movement and participants have to adapt to a novel visuo-motor behaviour (Hagura et al., 2007).

It has been suggested that this increased activation in the parietal cortex, present during visual and proprioceptive mismatch, could be a compensatory mechanism that resolves the perceived incongruence by creating a proprioceptive shift in perceived hand location (Clower et al., 1996). Although proprioceptive shifts have often only been observed when there is a spatial separation such as in a prism adaptation task, or muscle vibrations which can induce an illusory sense of body movement (Guinet & Michel, 2013), the notion that the parietal cortex is responsible for adapting to this incongruence could be applied to a temporal displacement.

Furthermore, the right PPC has been shown to have a significant increase in cerebral blood flow during motor learning. Specifically this was illustrated in a visually guided pointing task in which participants had to adapt to a 60° rotation. The authors concluded that their task provided evidence that the PPC, in order to compensate for any visual

perturbations, plays an important role in the remapping of visuo-motor co-ordinates (Inoue et al., 1997). This remapping is evident in the after effects of prism adaptation tasks in which individuals continue to mis-reach as a result of the adaptation (Redding & Wallace, 2006).

Additionally, the parietal lobe has been implicated in the role of agency with evidence suggesting that the application of TMS led to participants being more likely to misattribute agency to a computer when viewing a virtual hand (Preston & Newport, 2008). They concluded that this was evidence of a neural comparator in assessing feelings of agency over a limb. Similarly, MacDonald and Paus (2003) had participants perform a task in which they had to identify whether there was a visual delay added to their movements of a virtual hand. When rTMS was applied to the superior parietal lobule participants were less able to determine if there was an asynchrony when they made active movements. This again implicates the parietal lobe in creating a sense of agency.

tDCS has a history of being used to investigate motor functions. Usually this is done through measuring MEP's after stimulating areas of the motor system using tDCS and Transcranial magnetic stimulation (TMS) (Furubayashi et al., 2008; Lang, Nitsche, Paulus, Rothwell, & Lemon, 2004; Nitsche & Paulus, 2000). However, it has been suggested that significant changes in MEP's after tDCS in the motor cortex occur because the participants were not readily using that area when stimulation was happening, i.e. increases in excitability are more prominent when an underactive area is stimulated than when task demands are already increasing activity in that area. This is unlike tDCS studies investigating cognitive tasks as the participant would already have strong activation in the region being stimulated due to task demands. This critical difference between motor and cognitive tDCS studies could be the reason why polarity specific changes aren't always observed in cognitive studies due to activation in a region already being at its peak (Jacobson et al., 2012).

Although the task used in the present study was a motor task, the aim was not to directly impact motor actions, but to change the way the virtual

hand was perceived by maintaining body ownership and agency over the hand, despite the added visual latency. If ownership and agency could be maintained over the hand, through altering the way the visual and proprioceptive senses are integrated, then the way the participant performs the reaching task may not be different to baseline. To do this stimulating the PPC seemed the best course of action.

Previous research that has stimulated the PPC using TMS has demonstrated a disruption in its ability to update path corrections to shifting targets (Desmurget et al., 1999), eliminated multisensory enhancement between vision and touch (Pasalar et al., 2010), cause interference with remapping of visual and tactile information when limbs are repositioned (Bolognini & Maravita, 2007) and has been shown to disrupt synaesthesia (Muggleton, Tsakanikos, Walsh, & Ward, 2007). All these examples demonstrate that non-invasive brain stimulation to the PPC has an effect on sensory integration across various tasks. With a visual delay in our task creating a discrepancy between visual and proprioceptive inputs, the PPC will be important in the processing of this. It is hypothesised that tDCS will have a similar effect in modulating the effectiveness of sensory integration, with polarity specific results.

Due to evidence that the PPC plays a role in resolving sensory incongruences, anodal stimulation to the PPC, through increasing excitability, was expected to increase the PPC's efficiency and as a result see improvements in performance across lag conditions. Conversely, cathodal stimulation, through decreasing excitability, was hypothesised to perhaps disrupt sensory integration further or inhibit any compensatory mechanism resulting in the added 150ms lag having a more detrimental effect on performance than anodal and sham stimulation. Therefore in relation to sham, anodal stimulation was expected to see improvements in performance, while cathodal could pose a detriment. Alternatively, cathodal stimulation could result in an improvement in performance if the two sensory inputs are perceived as more distinct instead of being combined which could lead to a stronger reliance on proprioceptive information while disregarding the erroneous visual input.

As in the previous experiment, participants were expected to complete a reach to target task whilst wearing a motion sensor to record their movements, either with 0ms lag added or 150ms as this was the critical point discovered in chapter 6. Unlike chapter 4, stimulation was given during the task ('online') firstly due to time constraints, but also due to evidence suggesting a stronger facilitation on motor learning compared to offline application (Besson, Perrey, Teo, & Muthalib, 2016).



## Methods

### Design

The experiment had 2 independent variables, Stimulation Polarity (3 levels; anodal, cathodal, and sham) and Temporal Perturbation (2 levels, 0ms and 150ms). The dependent variables were a variety of kinematic measures including Movement Time (MT), Peak Velocity (PV), percentage of time in the deceleration phase (%DP), Time to Peak Velocity (TTPV), Angle error, Distance error, and Total error. Similarly to chapter 6, practise trials were not analysed.

### Participants

Participants were recruited through the use of advertising posters placed around the University of Nottingham Campus. Upon emailing to express interest in the study participants were given an information sheet and a tDCS screening questionnaire (appendix 3) to complete and return before continuing with recruitment to ensure participants safety before receiving the stimulation. Participation was required for 3 sessions as all participants would be receiving each type of stimulation (anodal, cathodal and sham). 23 participants were successful recruited with ages ranging between 20 and 28 ( $M=23.40$ ,  $SD=1.92$ ), 13 were female.

### Stimuli and Equipment

The stimuli in this experiment were identical to that chapter 6, please see this chapter for full details. In summary this included 6 red circular targets appearing within the MIRAGE workspace for the practise trials, followed by 4 new target locations for the main reaching task. The Polhemus Liberty Motion Tracker was also used as in the previous chapter. A sensor was attached to the participant's index finger and recorded their movements within the workspace, for more details see chapter 6.

### tDCS parameters

Simulation was 'online' meaning it was applied for the duration of the behavioural task; 12 minutes. The target region was the right posterior parietal cortex (PPC) whilst the reference electrode was positioned over the contralateral forehead region. The 10:20 EEG system was referred to

for accurate measurement of each participant's head to locate the target region, close to P4. The PPC should be located approximately 1cm above P4 (Gallace et al., 2014).

Current density calculations were performed prior to testing (current strength/electrode size). This was to ensure the stimulation parameters were within recommended levels as described in chapter 4.

Electrode sizes and stimulation parameters were identical to that in chapter 4, with the only difference being 'online' as oppose to 'offline' stimulation and the duration of stimulation lasting 12 minutes rather than 10. Length of stimulation should not affect current density or performance due to the online method. The only thing an increased stimulation time would change would be the duration of after-effects (Nitsche & Paulus, 2001).

### **Procedure**

Participants placed their right hand inside the MIRAGE and viewed the virtual representation through the window as it appeared in its veridical location. The motion sensor was attached to their index finger just as in chapter 6. They then completed the calibration process which involved them placing their finger on each target in turn and keeping it there for 10 seconds. Once this process was complete the tDCS set up could begin. This involved their head being measured with a measuring tape and the experimenter marking small red dots on the scalp to locate the correct target region. This involved following steps to locate key markers on the 10:20 system and calculating distance percentages between markers to find P4.

The target electrode was then held over the target region by the experimenter while the participant pulled on the neoprene cap securing the electrode in position. The reference electrode was then placed under the cap on the contralateral side of the forehead. The stimulation was then initiated and checked to ensure impedance was not too high and the stimulation had not failed. The task was then immediately initiated in which targets appeared in the MIRAGE workspace and participants

made simple reaching movements towards them, returning their hand to the starting position each time. They responded to 30 targets for the practise, and then immediately began the main stage (LAG) in which they responded to 4 new target locations with a total of 40 targets appearing. Participants completed the task with both no added delay, and 150ms added perturbation. The order of these was counterbalanced across sessions.

On average stimulation finished precisely on time with the end of the behavioural task, however in some cases participants were faster in their movements and finished slightly before the end of the stimulation. Participants were not debriefed until after all their 3 sessions so as not to influence the results in any way. Each participant returned for all 3 sessions in which they received each type of stimulation polarity, anodal, cathodal, and sham, counterbalanced across participants. The same task was used for each session with the only difference being the stimulation polarity received. Testing sessions were separated by at least 7 days in order to avoid any risk of lasting effects of the stimulation.

## Results

Kinematic data were analysed for 2 conditions, (0ms LAG, and 150ms LAG) across each stimulation polarity (anodal, cathodal, and sham), practise movements were not analysed. It was hypothesised that stimulation to the PPC could alter perception of the virtual hand and in turn effect the participants' movements. To test this hypothesis, results from the active stimulation conditions were compared to the sham condition for both the baseline and 150ms conditions.

Every individual trial was inspected, with the beginning of each movement being the closest frame to 50ms, and the end of each movement. Targets appeared for a maximum of 2 seconds meaning movements to targets had to be made within this time.

### **Movement time**

Movement time refers to the total amount of time that the participant took to reach the target once they began moving faster than 50ms. Trials were individually inspected to ensure that the start and end of each movement was correct.

A 2x3 repeated measures ANOVA comparing the effect of delay across stimulation conditions (comparison to sham would be illustrated in simple contrasts if main effects were found) showed a violation of sphericity for the interaction only and therefore the Huynh-Feldt correction was applied for the interaction,  $X^2(2) = 6.83$ ,  $p = .03$ . No main effect of stimulation polarity was shown,  $F(2,44) = .55$ ,  $p = .58$ ,  $\eta_p^2 = .02$ , but a highly significant main effect for delay was found,  $F(2,44) = 21.22$ ,  $p < .001$ ,  $\eta_p^2 = .49$ , suggesting stimulation did not alter movement times but an added delay of 150ms made participants significantly slower, supporting previous results from chapter 6. However no significant interaction was found,  $F(1.57,34.44) = 1.41$ ,  $p = .26$ ,  $\eta_p^2 = .06$ . (Figure 7-1).

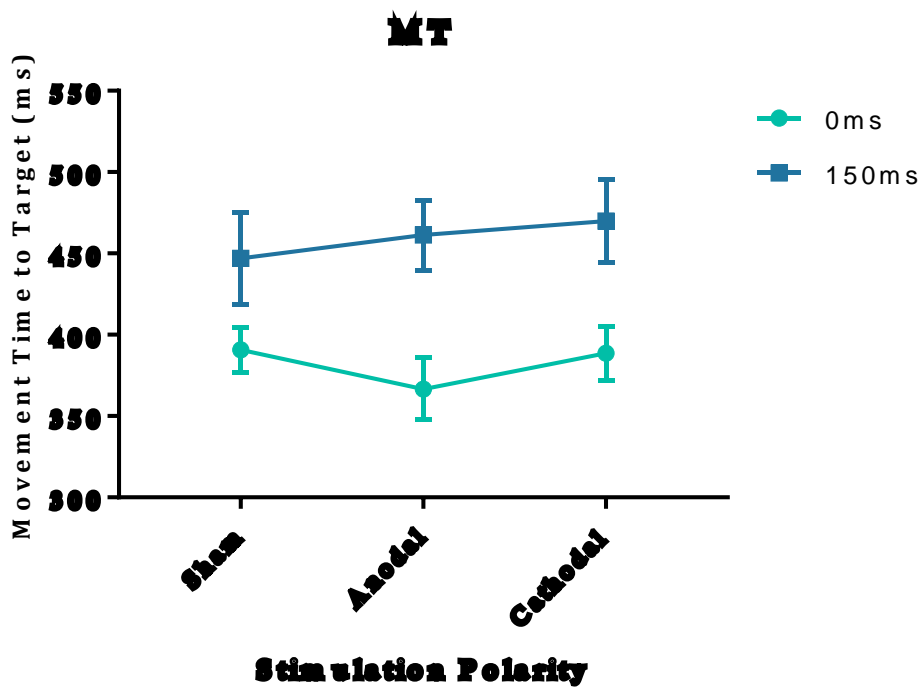


Figure 7-1: Movement time to target. Separate lines show 0ms and 150ms delay conditions, plotted across sham and both active stimulations.

### Peak Velocity

Peak velocity refers to the maximum velocity reached during the movement. A 2x3 repeated measures ANOVA showed no significant main effect of stimulation polarity,  $F(2,44) = .19, p = .83, \eta_p^2 = .01$ , but did show a significant main effect of delay,  $F(1,22) = 16.68, p < .001, \eta_p^2 = .43$ . However no interaction was shown,  $F(2,44) = .19, p = .83, \eta_p^2 = .01$ , suggesting that peak velocity differed depending on the delay but stimulation had no effect. The means show that peak velocity was higher for the zero delay condition ( $M=1152.69, SE=53.27$ ) than 150ms ( $M=1043.30, SE=52.18$ ).

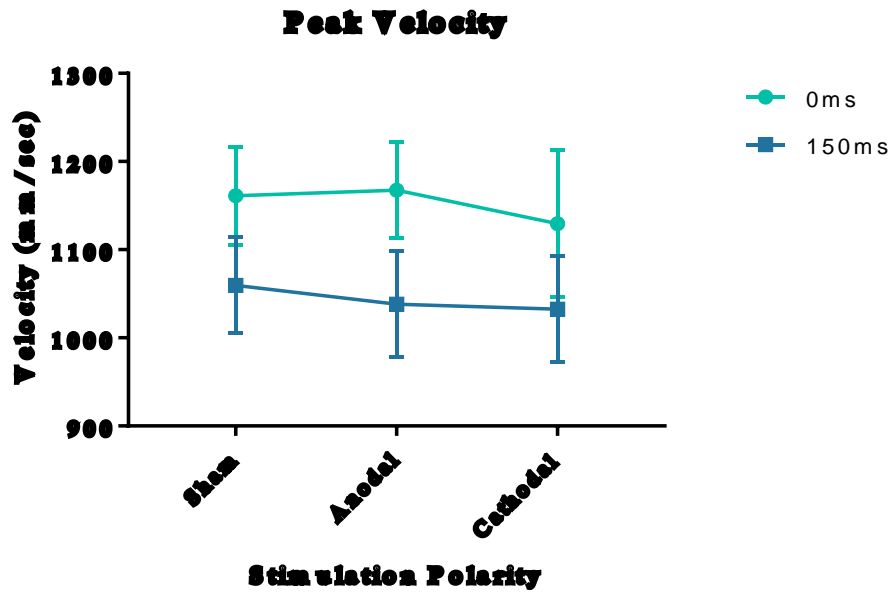


Figure 7-2: graph shows significant main effect of delay in which peak velocity was higher in the 0ms condition. The addition of 150ms delay meant participants travelled slower.

### Time to Peak Velocity

The amount of time taken to reach peak velocity was compared across stimulation and delay conditions. Results showed a violation of sphericity for the interaction term and therefore the Huynh-Feldt correction was applied. No main effects were shown, for stimulation polarity,  $F(2,44) = 1.26$ ,  $p = .29$ ,  $\eta_p^2 = .05$ , nor delay  $F(1,22) = .58$ ,  $p = .46$ ,  $\eta_p^2 = .03$ . The interaction was also not significant,  $F(1.55,34.01) = 2.02$ ,  $p = .16$ ,  $\eta_p^2 = .08$ . These results suggest that neither stimulation polarity nor delay affected the time take to reach peak velocity.

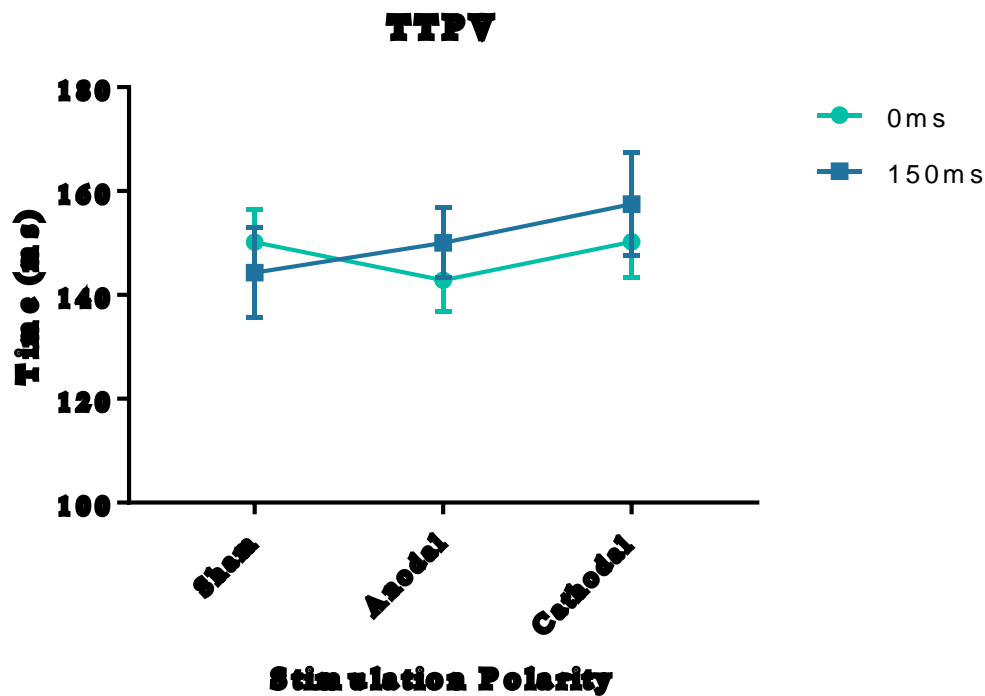


Figure 7-3: Time to Peak Velocity across stimulation conditions, separate lines represent delay conditions. No main effects, nor an interaction was significant.

#### Percentage of Time in the Deceleration Phase

This measure is considered a measure of task difficulty, with a longer percentage of time decelerating indicating participants are slowing down sooner, perhaps in order to be more accurate at the cost of speed.

Results of the ANOVA showed a significant main effect for delay  $F(1,22) = 39.51, p < .001, \eta_p^2 = .64$ , but not for stimulation polarity,  $F(2,44) = 1.21, p = .31, \eta_p^2 = .05$ . The interaction was also non-significant,  $F(2,44) = 4.32, p = .56, \eta_p^2 = .03$ , suggesting that stimulation did not significantly alter the percentage of time in the deceleration phase depending upon delay condition. (Figure 7-4).

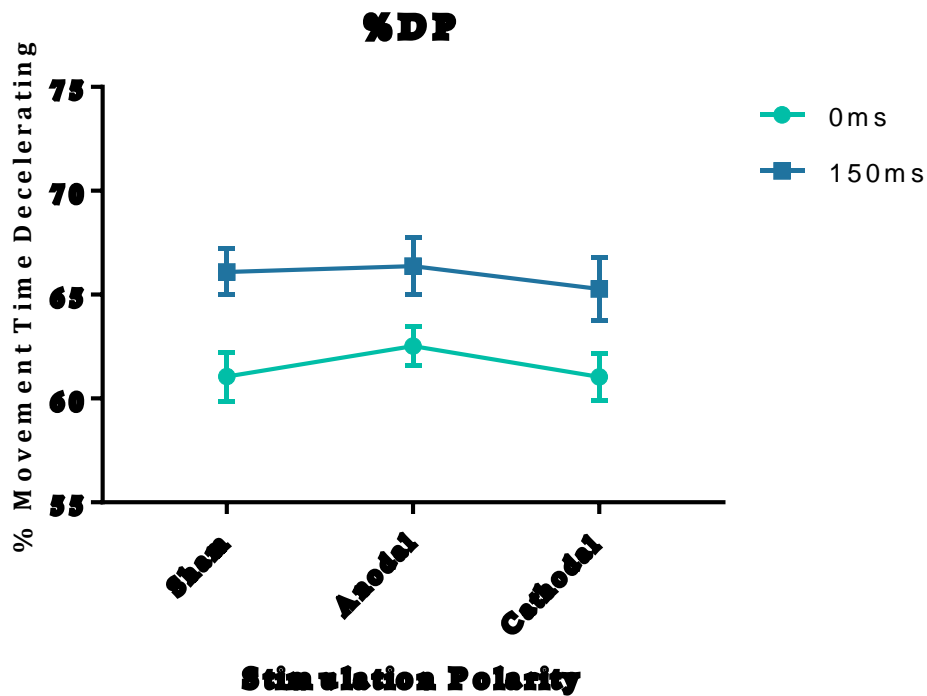


Figure 7-4: Percentage of time participants spent decelerating in each delay and stimulation condition. Significant main effect of delay only. Higher percentage of time spent slowing down when there was an added delay.

### Angle Error

This measure indicates how accurate their reaching movements were at landing in line with the target. Sphericity for the interaction term was violated and therefore the Greenhouse-Geisser correction was used for this measure,  $X^2(2) = 13.94$ ,  $p = .01$ ,  $\epsilon = .67$ . The results of the repeated measures ANOVA showed no main effect of stimulation polarity,  $F(2,44) = 1.96$ ,  $p = .15$ ,  $\eta_p^2 = .08$ , but did show a main effect of delay,  $F(1,22) = 9.07$ ,  $p = .046$ ,  $\eta_p^2 = .17$ . Results also showed a non-significant interaction,  $F(1.35,29.63) = 3.76$ ,  $p = .051$ ,  $\eta_p^2 = .15$ , (Figure 7-5).



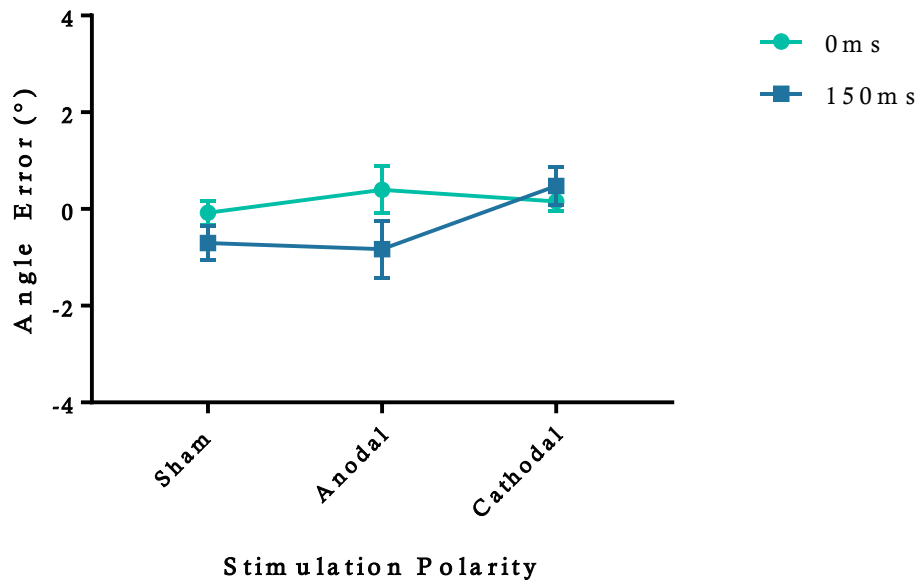


Figure 7-5: Amount of angle error across each stimulation polarity for each delay condition. Main effect of delay only.

### Distance Error

This refers to the difference between the distance from start position to target, and start position to end finger position, regardless of angle information. Moving further than needed resulted in a positive number, while an undershoot produced a negative result.

The results of the ANOVA showed a significant main effect of delay on amount of distance error,  $F(1,22) = 9.11, p = .006, \eta_p^2 = .29$  but no main effect of stimulation polarity,  $F(2,44) = 1.20, p = .31, \eta_p^2 = .05$ . There was also no significant interaction,  $F(2,44) = 2.13, p = .13, \eta_p^2 = .09$ . Therefore illustrating that there was a significant overshooting for the 150ms condition ( $M=8.31, SD=1.39$ ) than for 0ms ( $M=4.24, SD=.80$ ).

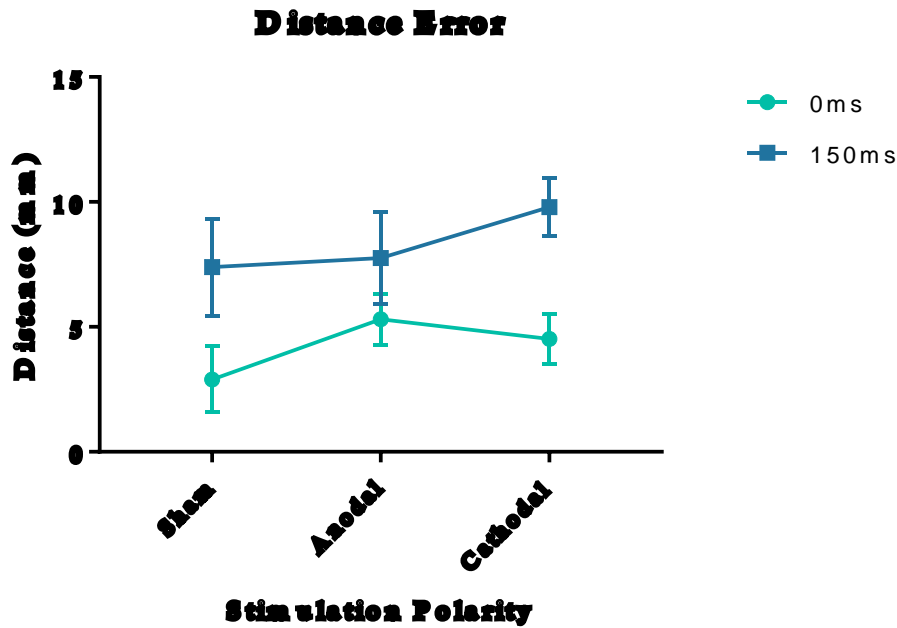


Figure 7-6: Distance error showing a main effect of delay with the 150ms condition resulting in larger distance errors. SEM bars displayed.

### Total Error

Total error refers to the average distance from the target that participants have reached to, regardless of angle.

Mauchley's test showed a violation in the assumption of sphericity for stimulation polarity  $X^2(2) = 20.72$ ,  $p < .001$ ,  $\epsilon = .62$ , resulting in the Greenhouse-Geisser correction being used.

The ANOVA produced a significant main effect of delay, again replicating what was found in the previous chapter,  $F(1,22) = 90.24$ ,  $p < .001$ ,  $\eta_p^2 = .80$ . However no main effect of stimulation polarity was observed,  $F(1.23, 27.04) = .59$ ,  $p = .48$ ,  $\eta_p^2 = .03$ , nor was there an significant interaction,  $F(2,44) = .61$ ,  $p = .55$ ,  $\eta_p^2 = .03$  indicating participants were more accurate in hitting the target when there was no delay and stimulation had no effect on accuracy.

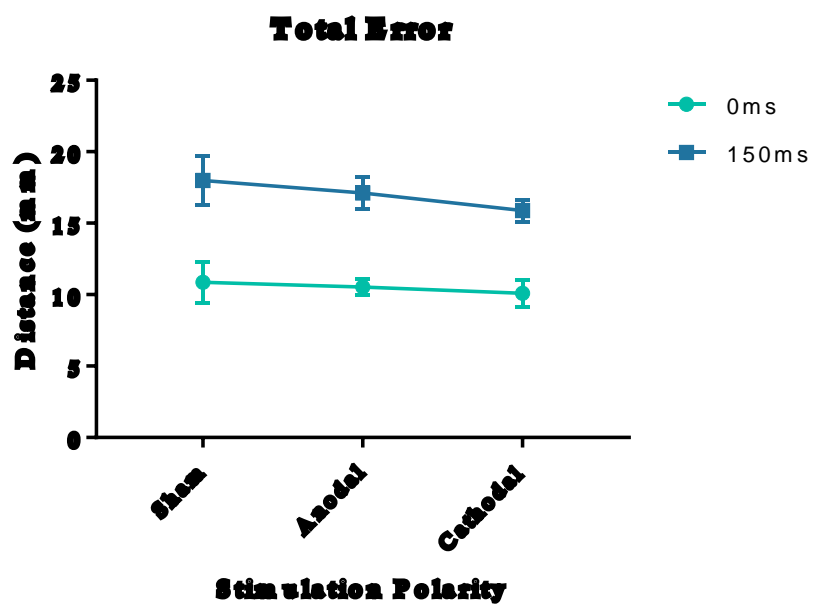


Figure 7-7: Shows main effect of delay, 150ms condition has significantly more error. Distance refers to distance from the target regardless of direction across each stimulation condition.

## Discussion

The results of this experiment highlight how participants make movements in a virtual environment and how this may change as a result of non-invasive brain stimulation. Overall the results have not shown any significant effects of tDCS in altering kinematic performance, with or without a delay.

Movement time, peak velocity, and %DP all showed a significant main effect of delay, but not stimulation polarity. Taken together, these results show that participants are taking longer to make the whole movement, achieve a lower peak velocity, and spend a higher percentage of time slowing down when there is an added delay of 150ms. This replicates the data collected in the previous chapter and supports our hypothesis that 150ms is a large enough temporal delay to create changes in movement profiles. The data highlights that the delay likely increased task difficulty and movement uncertainty.

TTPV did not result in any main effects, this perhaps suggests that the added delay did not influence the beginning stages of the movements. Additionally the target distances did not vary between 0 and 150ms conditions, therefore TTPV would not be expected to change as difficulty in maintaining accuracy is only apparent when slowing down the movement to touch the target.

Taking distance, angle, and total error together they show that having an added lag of 150ms meant participants were less accurate at reaching to the target than the 0ms added condition. Distance error results suggests that on average participants reaches landed slightly past the targets. It could be argued that in the presence of a visual delay participants are likely to overshoot slightly as the hand appears further from the target than it really is for the duration of the movement.

It was hypothesised that tDCS would alter the way visual-proprioceptive information was being integrated. However as no main effects or interactions for stimulation condition were found our results show tDCS was not sufficient in modulating this. A difference was expected to be

found due to the PPC being more active when there is a sensory incongruence present (Clower et al., 1996), such as in the present task with the added delay. Modulation to this area was therefore expected to interfere with a possible compensatory mechanism, or improve its efficiency.

Results showed that tDCS did not change kinematic performance, or overcome the differences created by having a 150ms delay. So although the PPC has been shown to be responsible for sensory integration across a variety of tasks (Desmurget et al., 1999; Muggleton et al., 2007; Pasalar et al., 2010), the results here show that tDCS was unable to sufficiently modulate the integration of visual and proprioceptive inputs. Since tDCS was not shown to successfully modulate task performance as a result of PPC stimulation, yet in chapter 4 spatial discrepancies were modulated, is a possible indication that temporal asynchrony alone is not reliant on PPC activation. The compensatory mechanism that attempts to rectify sensory incongruence may not have been sufficiently probed by our temporal task as other modalities were still providing enough sensory information about the hand, i.e. the hand was spatially congruent and appeared visually as they expected. This previously observed PPC activation may only be applicable when there are multiple conflicts in sensory information.

More recent literature has suggested that variability within the sample, and more interestingly within individuals, could be a significant factor in the outcome of a tDCS experiment and its reliability. Obviously anatomical variations across participants creates a problem with reliability for tDCS as the target region may not be located accurately across the sample (Datta et al., 2012), although the spatial resolution of tDCS is moderately low (Woods et al., 2016). However this could be overcome through the use of neuro-navigational software that uses individual brain scans to locate target regions in each person. For the present experiment this was not possible. Despite this, it is likely that the PPC was still being stimulated across all participants due to using the

10:20 EEG system to measure each participants head, and due to the size of the electrode that would have covered the region.

Inter-subject consistency has been shown to vary in multiple recent studies. Dyke, Kim, Jackson and Jackson (2016) tested the effects of stimulation at 2mA and showed that anodal stimulation did create an excitatory effect across the group, but this was not reliable within the same participants across separate testing sessions. As for cathodal stimulation they found that cortical excitability was not significantly modulated at group, nor individual level. This is consistent with previous findings that anodal stimulation did not create a reliable effect within the same individual at 0.5mA stimulation (Chew, Ho, & Loo, 2015), but reliable effects were found for 1mA (López-Alonso, Fernández-del-Olmo, Costantini, Gonzalez-Henriquez, & Cheeran, 2015). The discrepancies in the literature highlight the unreliability of tDCS, likely due to not being able to ensure a consistent neuronal resting state across participants at the start of each session. Reliability at 1.4mA has not specifically been investigated but as it lies between 1 and 2mA it is likely that anodal stimulation at least may create consistent results, although cathodal stimulation may be less reliable.

However new research might offer ways to overcome these inter-subject differences. The problem at hand is the differences between participants in terms of the amount of neural activity in the target region at the moment they receive stimulation. Homeostatic plasticity refers to the amount a region can change in terms of excitation and inhibition depending on its current state. One study investigating how tDCS might affect homeostatic plasticity showed that a region could be primed so that anodal stimulation for example could create both an excitatory and an inhibitory response. The study showed that applying two identical sessions of stimulation resulted in opposite results depending on the amount of time between sessions. A break of only 3 minutes, while after-effects are still present, meant the second session created the opposite result to the first (Fricke et al., 2011). This research could be vital for how future tDCS experiments are carried out. Its findings highlight the

importance of ensuring a stable baseline across participants or risk having opposite effects within the same polarity. One way of achieving this could be through using TMS at the start of sessions, however this would likely mean that only one polarity would have an effect but may be a good starting place for future work.

One key difference between this experiment and the one described in chapter 4 is the online method for the application of tDCS. By applying the stimulation for the duration of the task any behavioural changes should be immediate rather than relying on the presence of after-effects. This method was used for the present study primarily due to time constraints. Due to having 4 blocks of testing (2 for each delay, practise and LAG) this would have required 20 minutes of after-effects which is thought to be created by 9 minutes of stimulation (Nitsche & Paulus, 2001). However due to the effects declining over time it was decided that online stimulation might be more effective. An online design also ruled out any unwanted effects caused by anything the participant engaged in during stimulation prior to task completion. Different polarity effects have been demonstrated depending on the task completed during stimulation prior to the main experimental task (Nozari, Woodard, & Thompson-Schill, 2014) therefore online stimulation offers a more controlled method. Therefore it is not believed that an offline method would have produced significantly different results.

The present study targeted the PPC in efforts to modulate the way visual and proprioceptive information was being integrated due to the asynchrony created by the additional delay. However it is possible that stimulation of areas of the motor cortex could have modulated participants' movements. Previous research has demonstrated that stimulation to the motor cortex can effect movement adaptation in novel settings (Hunter, Sacco, Nitsche, & Turner, 2009), premotor cortex stimulation can disrupt audiotactile integration in relation to the hand (along with the PPC) (Serino et al., 2011), and abolish the inhibitory effect of the motor representation of the hand in M1 when stimuli are within near hand space (Avenanti et al., 2012) thus suggesting a role in the

remapping of representations relating to spatial processing. Furthermore it is widely accepted that the PPC is part of a larger network responsible for the processing of peri-personal space (Avenanti et al., 2012; Magosso, Zavaglia, Serino, Di Pellegrino, & Ursino, 2010; Noel et al., 2015) suggesting that modulation at another stage could potentially be more effective. This evidence suggests that regions of the motor cortex could be a viable alternative for stimulation to potentially overcome difficulties in performance when a lag is present.

An idea worth investigating in the future may be adding a trial at the end of the perturbation trials where participants make a couple of reaching movements with the lag turned off. This would show whether they immediately adapt back and whether they had in some way adapted to the previous incongruent visual information. It could also show if the stimulation had effected their ability to adapt in a different way to what has been measured in the present study. For example, if the lag is suddenly removed anodal stimulation may mean they adapt more quickly as they're better able to process the change between incongruence and congruence. Switching between lag and no lag could show a change in how quickly they're able to adapt.

The results of this study confirm what was shown in chapter 6 that a temporal perturbation of 150ms is sufficient to change movement profiles. A more direct disruption to the PPC by means of TMS could highlight whether this area is important for changes to be seen in the current paradigm, or confirm that temporal asynchrony alone does not heavily rely on PPC activation. However it is likely that a disruption would not help overcome the issue of lag. On the other hand as suggested earlier in this chapter a disruption could mean participants are able to rely solely on the more reliable proprioceptive information and improve their accuracy. In conclusion this study has been able to replicate results showing that a delay of 150ms degrades movement performance. It has also shown that tDCS to the PPC is not sufficient to overcome these changes, however this study may be replicated with the addition of methods to prime the cortex allowing more reliable polarity specific effects to be observed.



Additionally due to significant changes observed in chapter 4 through stimulation of the PPC we know that modulation of this area can impact the processing of peri-hand space although perhaps the premotor cortex may be a better site for observing changes related to movements in a novel environment.

## Chapter 8 General Discussion

The experiments presented in this thesis have furthered investigations in to the processing of near hand space by firstly illustrating the presence of an NHE in a virtual environment using a virtual representation of the hand, and second shown that neuromodulation to the PPC may be changing the processing of space around the hand when sensory inputs are incongruent. Furthermore the sole influence of hand fidelity on the NHE does not appear to be critical for success, while temporal lag is detrimental to kinematic performance when lag is above 75ms. This chapter provides a summary of the overall findings and evaluates their contribution to the literature while outlining possible future directions for this area of research.

### *Spatial Incongruence*

The results of the pilot experience described in chapter 2 confirmed the findings of Reed et al. (2006) and showed that a facilitation for near targets compared to far hand targets was present. Furthermore, that this was specifically related to the hand as this effect was not observed when the hand was replaced by a block.

The use of the MIRAGE to spatially separate the visual and proprioceptive inputs covertly allowed us to examine the effect of each modality on the representation of peri-personal space. The results presented in chapter 3 suggested that with the initial sensory incongruence peri-personal space appeared to have expanded to compensate for the noise as demonstrated by a decrease in reaction times of both near and far targets. This decrease suggested that both targets are being perceived as relatively closer within the space and suggests that targets at an even further distance may then be responded to in a similar way to far targets before the separation, and possible expansion of space, began. Second, at approximately 6-8cm of separation reaction times began to return to normal perhaps illustrating the formation of two zones of space rather than an expansion. This supports research showing the formation of two

zones after the use of tools (Holmes, 2012; Holmes, Calvert, & Spence, 2004), as it could be argued that the visual representation of the hand is now seen as a tool, while the real hand location is still perceived as the primary effector. In future it may be interesting to examine whether the same neurons respond to stimuli near the visual hand as to the real hand location. Presumably the same set of neurons are involved but somehow have remapped to enable responses to two locations.

Interestingly, chapter 3 saw a change in reaction times to far targets more so than near. This arguably supports the m-cell account by showing a stronger trade-off between near and far targets. It could be that at 2cm away from the tips of the fingers the near targets could not be further facilitated in terms of reaction times, however the sensory incongruence might have further prioritised the m-pathway in order to prepare for making visually guided movements resulting in a cost of processing the far targets. Alternatively the spatial separation itself promoted a visual dominance as suggested by Congedo et al., (2006). This pattern of results was not fully replicated in chapter 4 as the difference between near and far remained more stable while overall reaction times improved, initially peaking at 4-6cm, similar to chapter 3.

Results in chapters 3 and 4 suggest an initial increase in peri-personal space (perhaps caused by an increase in the vRFs of bimodal visual tactile neurons) followed by reaction times increasing again suggesting the formation of two distinct zones. However reaction times to targets appearing at a distance of 4-6cm were not tested again when the hands were fully separated. It might be that targets at this distance still show a stronger facilitation than targets presented at any other point. This could be due to a new (and sole) representation of the hand being created that lies somewhere in between the two extreme locations (Ratcliffe & Newport, 2016). This may have occurred due to the repetitive nature of the adaptation allowing the brain to create a representation of all the positions of the hand and anchor the focal point between the two hand representations.

Another explanation for why we saw a stronger facilitation for far targets at approximately 4-6cm of separation could be the result of bimodal neurons, but specifically the ones that move in the opposite direction to fraudulent visual input. As observed in Graziano (1999) when a fake arm was moved in a particular direction one group of neurons moved in the opposite direction to the arm. This could be happening in our adaptation. Potentially the amount of shift in the opposite direction is limited, or acts as a way to give a better estimate of true hand location by trying to encode proprioceptive information that is at odds with the visual input. Thus resulting in a stronger facilitation for targets appearing between the two sensory inputs as this is the perceived true location of the hand. This could also explain why Newport and Ratcliffe (2016) showed that after completing this spatial adaptation in MIRAGE participants judged their hands as being 60% towards the visual hand in the space between the two. Since the hand is always moving from the left towards the right, it makes sense that the updated representation is closer to the left side of space than located directly in between, and may not in fact represent a visual dominance.

In terms of what the tDCS findings suggest about the underlying mechanisms of the NHE it could be argued that cathodal stimulation inhibiting the localisation of the limb when no visual information is available, results in the vRFs of bimodal neurons unable to identify stimuli near the hand as they haven't been able to update their location, or what constitutes space near the hand. Furthermore, since cathodal stimulation seemed to make the near facilitation lessen for the real hand this would also support that both bimodal neurons and m-cell processing play a role. The biasing of the m-cell pathway is thought to be visually driven, meaning that when vision of the limb is removed the NHE could lessen, however since cathodal stimulation worsened it in the hidden condition this would suggest that a further detriment is being caused that is not dependent on vision. Therefore supporting claims made by Goodhew et al., (2015) that bimodal neurons may help update the positioning of the limb, while vision of the hand near stimuli may bias the

m-pathway for processing. However, as previously discussed, due to not being able to measure the resting state of neuronal activity prior to each stimulation session, the cathodal results may not be reliable.

Importantly the spatial experiments have demonstrated that the processing of peri-hand space does change if visual and proprioceptive inputs are not congruent. This has implications for the use of VR training in that if training involves controlling an effector that is not in the same location as their hand, this could lead to differences in the way they interact with the virtual space compared to the real world where these incongruences are not present.

### *Fidelity*

The result discussed in chapter 5 highlighted that changes in hand fidelity did not critically alter the processing of peri-hand space, when the hand is in the correct location, and there is a lag of no more than 10ms. Even when the hand did not match the body schema and visually only displayed 4 digits no significant changes to the processing of peri-hand space were observed. This evidence contradicts previous findings that have suggested that changes in texture (Haans et al., 2008), and hand shape (Tsakiris et al., 2010), significantly reduce both perceptions of ownership and the strength of illusions such as the RHI. However these differences in results are likely the effect of methodology dissimilarities, for example past research investigating changes in appearance of an effector have used stationary rubber hands or non-corporeal objects that are not in the same spatial location as the real hand, nor do they allow the user to obtain visuo-motor inputs. The MIRAGE allowed changes in hand fidelity to be created without altering any other sensory modality, and also provided the user with a brief amount of visuo-motor feedback. Therefore it could be argued that the experiment presented in chapter 5 explored the sole effect of changes in appearance of the hand and indicates that visual information is not as critical in maintaining a representation of peri-hand space as spatial changes (as observed in chapters 3 and 4). Deteriorations in ownership and illusion ratings in past research is

possibly the result of visual and spatial changes suggesting that if multiple inputs are congruent, hand representation can remain stable.

The results were unexpected as it was hypothesised that reductions in hand fidelity would reduce the NHE due to the strong influence of vision, in both the function of bimodal neurons and m-cell functioning. With Graziano, Cooke, and Taylor (2000) showing that bimodal neurons did not respond in the same way to an unrealistic fake arm as they did to a higher fidelity one it would suggest that reductions in fidelity in the present experiment would also not recruit the neurons. However as discussed in chapter 5 despite removing textual detail and changing the shape of the hand, what participants saw still resembled what they felt (even after the stroking adaptation in 4DIGIT). Therefore the stable NHE demonstrated across conditions highlights that when other senses are congruent visual information can be relatively unimportant. This has implications for training in that when developing a new VR or AR system the fidelity of the limb is not as crucial as other aspects such as spatial correspondence.

### *Temporal Lag*

The results presented in chapters 6 and 7 demonstrated that a temporal lag imposed on the movements of a virtual hand do not carry over when the hand is then stationary and alter the NHE. It was expected that a lag creating a sensory incongruence between vision and proprioception would potentially expand peri-hand space as a compensatory mechanism or cause the hand to not maintain ownership or agency leading to a reduction in the NHE. However no changes across any lag condition were observed suggesting if any changes are happening as a result of the lag, these do not carry over to affect the processing of space around the hand after. This suggests either that no changes are occurring as a result of added lag, or that if they are, peri-personal space adapts quickly to the new congruent sensory information.

Furthermore it was demonstrated that a lag of 150ms was sufficient to alter movement profiles including increasing overall movement times,

reducing accuracy to reach targets and taking longer to slow down suggesting the task was become significantly more difficult. The application of tDCS to the PPC to explore if lag could be compensated for to improve performance was unsuccessful. However targeting another brain region such as the motor cortex may have an impact on performance as discussed in chapter 7. In summary the results highlight that temporal lag between 75 and 150ms significantly reduces performance on a reaching task. Therefore VR and AR systems should endeavour to reduce lag to below these limits. These results are specific to a reaching task however, as in other contexts different limits have been demonstrated (Jay & Hubbard, 2005; MacKenzie & Ware, 1993; Pavlovych & Gutwin, 2012).

### *Implications of Results*

If we look at the pattern of results across all manipulations, spatial, appearance, and temporal, it could be argued that priority should be given to ensuring that what a user is controlling (e.g. a virtual limb) is in the same physical location as their actual limb as this incongruence appears to be the most detrimental and changes the way we process peri-hand space. This could suggest the use of augmented reality over VR as the user is able to view the world directly around them without being presented with conflicting spatial information.

The role of the body schema in influencing the representation of peri-hand space has also been explored throughout this thesis. Firstly the results of the spatial experiments have suggested that since two hand representations were able to create an NHE, the body schema is either not involved in maintaining a representation of peri-personal space or it is not the only factor responsible for creating it. This is because the body schema can only support one hand representation at a time, it is unclear from chapters 3 and 4 which hand was incorporated (Newport et al., 2010; Newport & Preston, 2011). Furthermore, it is thought that changes in kinematic performance can indicate changes in the body schema (Cardinali et al., 2009), however in chapter 6 a temporal lag reduced

performance on kinematic measures yet no changes were observed in the NHE. This could again suggest that changes to the body schema do not directly alter the processing of space around the hand, supporting the idea that the two concepts are dissociable. However the absence of change to the NHE could also demonstrate the adaptive nature of peri-personal space, by showing no changes once sensory information was congruent and the hand remained stationary.

In terms of supporting (or disproving) which theory best explains the NHE, chapters 2-4 best evaluate this. First, the pilot showed no differences in the NHE for the visual hand compared to the hidden real hand, suggesting that visual input is not the dominating influence. This goes against both the bimodal neuron theory and the m-cell account which both claim to be visually driven processes (Gozli et al., 2012; Graziano et al., 2000). If this were true we would expect to see a reduction in the NHE for the unseen hand. However, an overall improvement in RTs for the visual hand was observed in chapter 3. This overall facilitation for visual hand targets could be evidence that visual input is treated differently, or it could show that the visual hand is treated as a tool in addition to the real unseen hand and therefore assigned functional importance over the real hand. The suggestion that both theories are visually dominant may need adapting, perhaps they are both influenced by visual input, but also work on other factors.

The findings from chapter 4 that tDCS can modulate the NHE with the hands separated could suggest the involvement of both bimodal neurons and m-cell biasing since both are related to the PPC. Cathodal stimulation could have done several things including disrupt the ability of the PPC to resolve sensory incongruence, leading to a stronger reliance on visual information. Second, it could have disrupted the representation of the limb in space. This suggestion could imply that bimodal neurons are not solely responsible for the NHE as a reduction in the responses to visual stimuli would likely have been observed if limb position can not be accounted for. On the other hand, with limb position disrupted responses may have increased to the last known position of the hand (the visual



location). The RTs in chapter 3 that showed far target changes more so than near would suggest support for the involvement of m-cell biasing as they should allow a trade-off between near and far targets. The consistent facilitation of near hand targets could indicate their relative position within vRFs or the increased temporal sensitivity for stimuli for items closest to the hands (Abrams & Weidler, 2014). With evidence to support both it is unclear whether we can rule out one theory but I would argue that both bimodal neurons and m-pathway biasing are involved and perhaps support each other in providing a representation of the limb and the space around it. Proximity to the hand as recorded by the vRF could dictate the changes to temporal sensitivity. In terms of changes to peri-personal space, I would argue that upon initial separation of the hand in chapter 3 and 4, there is an expansion of the receptive fields of bimodal neurons to try to compensate for the sensory discrepancy. Following this, as the participant completed multiple adaptations a new (sole) representation of the hand is created 60% towards the visual hand (as measured by the hand estimation task). This could indicate a remapping of the neurons responses, to best respond to targets near this new representation and perceived hand location. This remapping could have been aided by the bimodal neurons that move in the opposite direction to the visual information and perhaps are tasked with trying to compensate for incongruent visual information to present a more accurate limb location.

In regard to reasons why tDCS was successful in modulating changes to the spatially separating hand, but not the temporally asynchronous hand, could lie in the inhibitory effect of cathodal stimulation. Chapter 4 highlights that cathodal stimulation may be impairing the PPC's ability to expand peri-personal space. However in the temporal experiment in chapter 7, no expansion of peri-personal space was expected to occur as spatially the hands are congruent. Alternatively, the temporal asynchrony was not as large an incongruence as the size of the spatial separation. In terms of relative sensory disruption the two are not completely

comparable. Therefore it's possible that larger temporal asynchronies may have been more likely to be effected by the tDCS.

The thesis as a whole has also built on the initial findings by Reed et al (2006) by demonstrating a facilitation for near hand targets in a virtual setting, furthermore has shown that even when no vision of the hand is available the unseen location of the hand is sufficient in generation an effect thus supporting previous research (Abrams et al., 2008; Adam et al., 2012). However by only using a reaction time task this thesis is unable to make conclusions pertaining to other recorded effects of proximity to the hand such as semantic changes or visual search. Nevertheless the results do provide a more valid exploration of the visual contribution of the limb by using real input rather than a prosthetic.

The experiments presented in this thesis also bridge the gap between using fake prosthetic hands, virtual hands, and the real hand. The visual representation created inside MIRAGE is a live video recording of the participant's own limb meaning it resembles the hand more so than a rubber substitute or generic virtual arm. At the same time it is not exactly the same as viewing the hand normally as it is not presented in colour. By having a more realistic representation than any previous work (excluding other work using the MIRAGE) we removed the confound of having to embody a new effector. With research showing conflicting evidence that the brain may (Perani et al., 2001) or may not (Makin et al., 2007) have different patterns of activation when viewing a fake limb, it was important to try and ensure that manipulated limb was as much like the real hand as possible to reduce the chance of any confounds. The use of MIRAGE therefore allowed the exploration of each associated issues in VR independently, something that has not been achieved before.

### *Reliability of tDCS*

The reliability of tDCS has been called in to question in recent reviews (Wiethoff, Hamada, & Rothwell, 2014). As long as a study is well controlled and planned, issues with the application should not be problematic, nor should the task be a confounding factor. The primary

issue more recently reported, and perhaps of some concern for the present research, is intravariability not just between subjects but within subjects. Wiethoff et al. (2014) found that 50% of their sample had no response to tDCS protocols highlighting the need to investigate what factors make people susceptible to cortical changes. For example, many different factors can influence cortical excitability other than non-invasive stimulation which may then alter the effects of the stimulation, such as the use of substances such as nicotine (Thirugnanasambandam et al., 2011), and time of day (Sale, Ridding, & Nordstrom, 2007). Specifically relating to brain stimulation factors such as age (Fujiyama et al., 2014; Moliadze et al.), and anatomical differences (Marom Bikson, Rahman, & Datta, 2012; Datta et al., 2012; Miranda, Mekonnen, Salvador, & Ruffini, 2013) have also created differences in the effectiveness of modulating cortical activity. However these factors may be appeased by selecting participants within a small age bracket, and using neuro-navigational tool to ensure stimulation to the same regions accurately.

Dyke, Kim, Jackson & Jackson (2016) investigated the reliability of tDCS within the same individuals over the course of multiple sessions. Importantly they found that neither anodal nor cathodal stimulation created reliable changes for the same individual across repeated sessions. The take home message here being that stimulation may change cortical excitability one session, but not the next, even for the same person. The factors mentioned above could be contributing to these changes, but when they are controlled such as the same time of day what else might be causing these results? For either polarity of stimulation to create changes the resting state of the area of targeted neurons must be balanced i.e. therefore allowing an increase or decrease. Studies have demonstrated the use of tDCS to prime the cortex prior to rTMS which can change a traditional inhibitory response to increase excitability and vice versa (Bocci et al., 2014). Thus demonstrating how the initial state of the cortex effects the outcomes of stimulation, this is known as homeostatic plasticity (Filmer, Dux, & Mattingley, 2014).

The effect of priming have been explored to assess homeostatic plasticity within the cortex and shown that the application of tDCS to the motor cortex can influence the direction of plasticity by subsequent TMS (Siebner et al., 2004). Specifically they showed that after anodal tDCS increased excitability the application of TMS caused a reduction in excitability, bringing levels back towards a baseline. They observed the opposite effect after the application of cathodal tDCS. This evidence clearly shows that the direction of excitability is dependent on the initial resting state of the neurons in the target region. This could explain why some studies have seen null effects of tDCS, as there may have been large variation in the directional effects across the sample.

The above evidence showing high variability across and within individuals in how receptive they are to tDCS, casts some doubt over the results presented in this thesis. If the experiments were to be repeated again, the variable effect of tDCS would suggest that we might not find the same pattern of results. However due to the counterbalancing of condition order and controls put in place such as returning for additional testing at the same time of day, these results may be reliable however the use of priming should be used in future to be more certain in the replicability. Furthermore, even if the direction of effects of tDCS can change based on initial resting states, the research presented here shows that stimulation can modulate excitability (and as a result task performance). Nevertheless, if running future experiments using tDCS I would use TMS prior to stimulation to prime the cortex so as to ensure the same resting state of the target region across participants.

In regard to further evaluating NHE theories, applying TMS or tDCS to disrupt/modulate different pathways could highlight whether the trade-off between near and far targets diminishes. If the m-pathway or the p-pathway were disrupted and changes to the NHE were not shown this could clarify whether bimodal neurons are more important while a lesser change could indicate that they both work together.

### *Improvements and Directions for Future*

To further evaluate some of the findings from the current experiments several future studies could be run. First, it would be worth exploring the notion that a new representation of the hand is being created between the two hands and acting as the sole neural representation. One way of demonstrating this would be to remove vision of the hands post adaptation and have targets appear on the location of the suspected new hand compared to other locations. Targets appearing nearest the suspected new hand should show the strongest facilitation. This could also be measured over time to see if the representation shifted back towards the proprioceptive input.

As mentioned in the introduction, it has been shown that when stimuli are presented in between both hands the graded nature of facilitation disappears, likely because of the contributions of each hand (Tseng & Bridgeman, 2011). With this in mind, another way to look at the contributions of the visual and real hands could be to do the spatial separation paradigm as described in chapter 3, but instead of having targets appearing in line with each hand, have multiple targets appearing at different distances between the two hands. Of course presently during the adaptation the hands spend most of the time overlapping meaning there is no space between them, however in the future with a larger version of MIRAGE a much larger separation could be tested. If visual and proprioceptive contributions are equal then the graded response to targets should not be observed, however if vision is dominant then a graded effect could be demonstrated. An even larger expansion could also highlight if there are spatial limits to this effect, or whether all space between the hands regardless of distance is processed as near hand space.

Third, to help distinguish further how the near hand facilitation works an experiment could be run in which the participant views their own hand in its correct location whilst responding to near and far hand targets, but with the addition of another person's hand placed opposite. If the facilitation is indeed dependent on feelings of ownership over the hand

and this is what shifts any receptive fields then it would be expected to only show a facilitation for targets near their own hand. The target near to the other hand would not be in graspable space for the participant and therefore would not need preferential processing to evaluate it, nor would it be considered a threat over the target appearing closer. On the other hand, viewing another hand could influence the location of receptive fields which would be shown by equal reaction times to both targets. However based on proprioceptive inputs the participant should be fully aware which hand is theirs and it would be predicted that only a facilitation for targets near their own hand would be observed. Nevertheless this paradigm could offer further insight into the NHE and could even be carried out with different hands that either resemble or are dissimilar from the participants e.g. feminine/masculine, larger/smaller.

For all of the experiments targets appeared red in colour. This was initially chosen to be high contrast with the surface of MIRAGE and stand out the most. However some evidence from the m-cell account has suggested that these cells may be inhibited by red light (Goodhew et al., 2015). Conversely it has also been suggested that m-cells rely primarily on rods (as oppose to cones) meaning they may in fact be colour blind. If this is the case then the colour of the targets should have had no confounding effect on reaction times, however as a consideration for the future it might be prudent to use targets of a different colour.

### *Summary*

In summary, the experiments presented in this thesis provide a new way of investigating changes in the processing of peri-hand space through the use of MIRAGE. It allowed the separation of visual and proprioceptive inputs to be measured alongside one another, without the use of a prosthetic limb, and is the first known research to examine what happens to peri-hand space as a gradual, covert separation occurs. It also provided the means to explore changes in hand fidelity without the confounds of embodiment of a fake, spatially displaced limb. Lastly, it allowed us to investigate incremental effects of lag on movement using a spatially

congruent and realistic representation of the participants own hand. By being able to manipulate just one of these factors at a time, this thesis has been able to demonstrate the contributions of each in being able to maintain a representation of peri-personal space. The results have highlighted at what points these factors may become an issue for performance using a VR/AR system and suggest that fidelity is not as important as temporal and spatial factors. The findings presented here also would suggest that peri-personal space can expand, perhaps as a compensatory mechanism when sensory information is slightly out of phase, and that this might be as a result of changes in the size of receptive fields of bimodal visual tactile neurons. Second, that the brain may recognise a repeated change between visual and proprioceptive information and attempt to adapt for this by creating a new representation of the hand through remapping perceived limb position and peri-personal space. In terms of how these findings impact upon current cognitive theories pertaining to the NHE, this thesis has suggested that bimodal neurons likely play a role in updating limb position and this in turn informs the boundaries of peri-personal space, yet the previous definition of a larger reliance on vision should be questioned and further evaluated. Our results also suggest the involvement of a biasing of m-cells due to the relative changes to far targets being observed. Therefore both theories should be combined to create a larger over-arching theory that explains more fully how the processing of peri-personal space changes for stimuli presented near the hands.

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## Appendices

### Appendix 1: Edinburgh Handedness Questionnaire

Name:

Date of Birth:

Gender:

Please indicate your preferences in the use of hands in the following activities by putting '+' in the appropriate column. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put '++'. If in any case you are really indifferent put '+' in both columns. Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets. Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

		LEFT	RIGHT
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking Match (match)		
10	Opening box (lid)		
i	Which foot do you prefer to kick with?		
ii	Which eye do you use when using only one?		

## Appendix 2: Hand Questionnaire (Chapter 3 & 6)

### Ownership

1. The hand I saw felt like it was part of my body.
2. The hand I saw belonged to me.
3. It felt as if I had more than one right hand.

### Agency

1. It felt like I was in control of the hand I was looking at.
2. It felt like my hand was out of my control.
3. It seemed as if the virtual hand had a will of its own.

### Presence

4. It feels like I am looking directly at my hand, rather than at a video image
5. I was controlling the hand I saw

### Size, shape & weight

6. My hand felt heavier than usual
7. My hand felt lighter than usual
8. My hand felt bigger than usual

### Feelings/sensations

9. I felt unusual sensations in my hand, such as tingling, itching numbness and/or burning.
10. I felt an ache or throbbing in my hand.

### Response scale:

-3    -2    -1    0    1    2    3

-3 strongly disagree.

+3 strongly agree.

0 Neither agree nor disagree

Appendix 3: tDCS Screening Questionnaire

**Transcranial Direct Current Stimulation (tDCS) Safety Screening Form**

***It is important that you answer all of the following questions truthfully.***

*If any of the questions/terms on this form are unclear, or if you are unsure how to answer them, please do not hesitate to ask one of the primary investigators of the study.*

	Yes	No
Have you ever had a seizure?		
Have you ever had a head injury resulting in a loss of consciousness that has required further investigation (including neurosurgery)?		
Do you suffer from Migraines?		
Have you ever been medically diagnosed with a neurological or psychiatric disorder?		
Do you have any metal in your head (outside of the mouth) such as shrapnel or surgical clips?		
Do you have any implanted devices (e.g., cardiac pacemaker, brain stimulator)?		
Do you have a skin condition on your scalp? (e.g. Psoriasis)		
Do you have a head wound that has not completely healed?		
Have you ever had an adverse reaction to tDCS?		
For female participants: Is there the possibility that you might be pregnant?		
Are you currently taking any prescribed medications, other than the contraceptive pill?		

The possible hazards of tDCS have been explained to me, and I understand that I can withdraw at any point for any reason, and that I do not have to disclose the reason(s) to the experimenter. By signing below I acknowledge that I understand this screening form and attest to its accuracy.

Participant's signature	Researcher's signature	Date

Primary Experimenter: Hayley Thair

Email: lpxht1@nottingham.ac.uk

#### **Appendix 4: Hand Questionnaire (Chapter 4)**

Ownership 1: The hand I saw felt like it was part of my body

Ownership 2: It felt as if the hand I saw belonged to me

Ownership 3: It seemed as if I had more than one right hand

Sensations 1: I felt unusual sensations in my hand such as tingling, itching, numbness or burning

Sensations 2: I felt an ache or throbbing in my hand

Hand moving (at end only): It felt as if my hand was moving

## Appendix 5: Adverse Effects Questionnaire

This questionnaire will be filled in before receiving tDCS stimulation and after.

Please enter a value from 1-10, ranging from absent to severe, in the 'Rating' space below in response to the question: "Do any of these statements currently apply to you?" It is important that you answer all questions truthfully:

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----



Do any of these statements currently apply to you?	Rating		Notes
	Before tDCS	After tDCS	
Headache			
Neck pain			
Back pain			
Blurred vision			
Scalp irritation			
Tingling			
Itching			
Increased heart rate			
Burning sensation			
Hot flush			
Dizziness			
Acute mood change			
Anxiety			
Others (specify in notes):			

**Appendix 6: Questionnaire (Chapter 5)**

Control/pre stroke	The hand I see feels like it is my hand
Control/pre stroke2	It feels like I only have 3 fingers and a thumb
Control/pre stroke3	The hand I see belongs to me
post stroke 1	It felt like one finger was being stroked
post stroke 2	it felt like more than one finger was being stroked
post stroke 3	It felt like I was missing my little finger
Sensations	I felt unusual sensations in my hand
Ownership 1	The hand I saw felt like it was my hand
Ownership 2	The hand I saw did not belong to me

-3 for strongly disagree, +3 for strongly agree