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Abstract

Hari and Jousmaki (1996) highlighted the distinction between personal space and peripersonal space in their finding that motor activity is initiated more efficiently in response to stimuli located on the responding limb as opposed to near the responding limb. Experiments conducted in the current thesis adapted the Hari and Jousmaki (1996) method in order to determine whether a similar bias could be associated with virtual limbs. These studies revealed that responses to a target located on a virtual limb under the constant reliable control of the individual are faster than responses to a target located near the virtual limb, irrespective of the visual appearance, spatial orientation, and spatial location of the limb. In the absence of control over the virtual object, these studies also found some evidence to suggest that the experience of tactile sensation from the virtual hand may result in a similar bias. Past research suggests that these findings may be a result of an attention bias towards the virtual limbs (Whiteley, Kennett, Taylor-Clarke, & Haggard, 2004); however, the evidence presented in this thesis cannot support an attention explanation thus it must be concluded that the on/off effect observed in this thesis is the result of compatibility between the stimulus and the response. This thesis discusses the implications of these findings to review the potential applications of this research from a theoretical and methodological perspective.

Preface

Concepts of self have been the subject of study in psychology for many years as an understanding of the physical body in relation to the external surroundings is paramount for successful functioning. Psychological research to date has investigated this comprehension of the body in space by attempting to construct a spatial map of the regions within and beyond the body in order to further understand how the body is represented in the brain. Chapter 1 presents research exploring concepts of space and schema related to the physical body of the individual. Research has proposed that spatial regions around the body can be dissected into personal space ('on body' space - within or on the body), peripersonal space ('near body' space - within the reach of the stationary body), and extrapersonal space ('far body' space - beyond the reach of the stationary body). Research has further proposed that an understanding of the body is formed through an internal representation described as a body schema. Concepts of personal space and the body schema can be closely related: our body schema refers to the component parts of our physical body (what we are) whereas our personal space is the spatial location of our physical body (where we are) and the combination of these two concepts allow us to establish a sense of self (who we are).

Chapter 2 investigates the potential flexibility of personal space and the body schema. Spatial coding and body schema have been described as malleable entities capable of plasticity under certain conditions. Research suggests that spatial coding may be flexible to the extent that objects located some distance from the body may be re-coded as though they are located close to the body and objects located close to the body may be re-coded as though they are located some distance from the body. Similarly, research proposes that the body schema is a flexible construct that may be projected to incorporate external objects (such as a tool) or retracted to acknowledge physical restrictions (such as an amputated limb).

Research conducted in this thesis aimed to investigate the flexibility of spatial coding and the body schema through the adaptation of the method designed by Hari and Jousmaki (1996). Hari and Jousmaki (1996) found that motor activity is initiated more efficiently in response to stimuli located on the responding limb as opposed to near the responding limb. They proposed that stimuli located off the body required additional processing unnecessary for stimuli located on the responding body and concluded that these findings demonstrate a type of spatial stimulus-response compatibility. An alternative explanation for these findings was proposed by Whiteley, Kennett, Taylor-Clarke, and Haggard (2004) who found that the bias towards stimuli located on the body remained when the participant was required to respond with the opposite hand through a forced choice key press. This design eliminated the possibility of a compatibility effect thus Whiteley et al (2004) attributed their findings to an attention bias toward stimuli located on the body. Further details relating to these two key experiments are presented in Chapter 3. Chapters 3 to 7 contain seventeen experiments exploring the difference between responses to stimuli located on a virtual limb and responses to stimuli located near a virtual limb.

Chapter 3 reviews the study conducted by Hari and Jousmaki (1996) to describe the design of the replications completed in the current thesis. Experiments 1 and 2 adapted the Hari and Jousmaki (1996) method to explore any bias towards stimuli located on a virtual body in a simulated environment in order to determine whether a similar bias could be associated with virtual hands. These studies found that responses to targets located on the virtual limbs were faster than responses to targets located near the virtual limbs and these findings were taken as tentative evidence for the projection of personal space to incorporate the virtual limb, or, alternatively, incorporation of the virtual limb into the body schema. In this context, 'incorporation' is operationally defined as the projection of personal space to space beyond the physical body or the alteration of the body schema to include objects not a part of the physical body.

Chapter 4 notes that the bias recorded in the previous chapter was specific to the virtual limbs as opposed to other virtual objects present in the simulation so it was argued that there must be a specific set of features to direct this bias toward the virtual limbs. Experiments 3 to 6 examine the roles of visual appearance and spatial location of the virtual limbs: Experiment 3 presents the virtual limbs as mirror images of hands; Experiment 4 presents the virtual limbs as feet; Experiment 5 presents the virtual limbs as cones; and Experiment 6 presents the virtual limbs some distance in front of the real limbs. The findings of these experiments reveal that there was enhanced processing for stimuli associated with the virtual limb, irrespective of the visual appearance, spatial orientation, and spatial location of the limb.

Chapter 5 discusses the issue of control with regards to personal space and body schema. Experiments 7 to 12 examine the role of control in the response preference for stimuli located on the virtual limbs: Experiment 7 investigates the absence of control by making the virtual hands immobile; Experiment 8 investigates the importance of predictability of control by making the movement of the virtual hands unpredictable; Experiments 9 and 10 investigate the flexibility of control by placing each virtual hand under the control of the opposite physical hand; Experiment 11 investigates the importance of the controlling limb by placing the virtual limbs under the control of the feet; and Experiment 12 investigates the potential for 'second-hand' control by placing virtual limbs under the control of a physical tool wielded by the participant. These studies highlight the role of control as a mediating factor in the bias towards stimuli located on the virtual limb: preferential processing of stimuli located on, as opposed to near, the virtual limb was dependent on the individual wielding consistent predictable control over the virtual limb in order to complete a specific task.

Chapter 6 explores the role of visuo-tactile feedback as a mediating factor in the preference for stimuli associated with the virtual limb: initial studies aim to determine whether tactile feedback can be associated with virtual hands (similar to the tactile feedback associated with fake hands in the rubber hand illusion) and subsequent studies aim to determine whether this experience can invoke preferential processing of stimuli located on the virtual hands in the absence of control. Experiment 13 adopts the method designed by Botvinick and Cohen (1998) to measure illusory tactile sensation associated with the virtual hand. The findings of this experiment reveal that the illusion of tactile sensation can be associated with virtual limbs following concurrent visual stimulation of the virtual hands and tactile stimulation of the physical hands. Experiments 14 and 15 investigate the effect of this experience on the subsequent responses to stimuli located on or near immobile virtual limbs. These studies offer some support to the suggestion that responses can be biased towards an object in the absence of control, provided that there has been prior experience of feedback from the virtual limbs.

Hari and Jousmaki (1996) suggested that their findings were due to a stimulus-response compatibility effect, whereas Whiteley, Kennett, Taylor-Clarke, and Haggard (2004) attributed their findings to an attention bias toward stimuli located on the body. Experiments 1 – 15 cannot provide evidence to support either theory as the findings of each experiment could equally be attributed to a compatibility effect or attention bias. Chapter 7 presented research to distinguish between these two possible explanations. Experiments 16 and 17 explored the detection accuracy of target letters located on or near the virtual limbs. The findings of these experiments could not support the attention bias explanation, as the results did not reveal that detection was significantly more accurate for letters located on the virtual limbs. It was, therefore, argued that the on/off effect observed in the virtual environment is the result of compatibility between the stimulus and the response.

It is concluded that there is a preference for stimuli associated with a virtual limb under the consistent, reliable control of the individual, irrespective of the visual appearance and spatial location of the limb. Chapter 8 argues that these findings suggest that the current definitions of personal space and the body schema may offer an inappropriate perspective of the representation of the body in the brain. Conventional theories relating to space and schema have suggested that the mind holds a relatively fixed internal representation of the body and the space occupied by the body. These definitions have been criticised by a number of psychologists (in particular, Holmes & Spence, 2006) for proposing an inexplicable homunculus in place of an explanation for the wide variety of behaviours under exploration. The current findings suggest that it may be more appropriate to define the internal representation of the body in terms of what is under the control of the brain. Perhaps the body schema does not exist per se, but rather the mind holds a dynamic framework of the objects under the control of the individual; most commonly the physical body as this is the object most often under control, but also flexible enough to incorporate any other objects controlled by the brain. The potential applications of this research are discussed in Chapter 8 with regard to the theoretical findings (bias towards stimuli located on external objects under the control of the body) and in Chapter 9 with regard to the methodological findings (responses to the virtual body can be similar to responses to the physical body).

Chapter 1

Space and Schema

Concepts of self have been the subject of study in psychology for many years as an understanding of the physical body in relation to the external surroundings is paramount for successful functioning. It is evident that the brain is capable of distinguishing the body from the surrounding environment: most people will experience an intuitive appreciation of the location of their own body relative to other objects in space. Research to date has investigated responses to stimuli located within and beyond the body in order to further understand how the body is represented in the brain.

Space: Divisions in Spatial Coding

Research investigating spatial understanding has dissected the area within and around the body in order to determine whether spatial coding for stimuli differs according to the location of the stimuli in relation to the physical body.

Brain (1941) reviewed case studies of patients demonstrating visual disorders as a result of right hemisphere damage to suggest that there may be specific systems for 'grasping space' or near body space and 'walking space' or far from body space. Of particular note, Brain (1941) reported one case of a patient who found it difficult to judge relative distances of objects located in the left visual field of walking space. This patient was unable to identify the nearer object when one item was located eight feet from his body and one item was located eighteen feet from his body. In contrast, the patient was capable of identifying the nearer object when both items were located approximately one yard from his face. This finding suggests that the patient had an intact system for locating objects in grasping space, but suffered damage to the system responsible for locating objects in walking space. Brain (1941) proposed that lesions closer to the hand area result in damage to the system for grasping space whereas lesions closer to the leg area result in damage to the system for walking space. Paterson and Zangwill (1944) also noted spatial distinctions in visual disorders following damage to the right hemisphere. They observed a specific difficulty in estimating the distance of near and far objects: near objects (approximately 250mm) resulted in a tendency to overestimate distance, whereas far objects (approximately 1000mm) resulted in a tendency to underestimate distance. They concluded that these findings support the theories proposed by Brain (1941) and they argued that spatial regions within and beyond reach of the body are under the control of different cortical mechanisms.

Research exploring spatial coding in relation to the body has also highlighted the distinction between the space within reach of the body and the space occupied by the actual body itself. Roland, Skinhoj, Lassen, and Larsen (1980) have argued for a neural distinction between intrapersonal space and extrapersonal space. It was noted that voluntary movements in intrapersonal space involve moving one body part relative to other body parts using the body itself as a reference system (proprioceptive and cutaneous feedback), whereas voluntary movements in extrapersonal space involve movements towards specific stimuli beyond the body using the environment as a reference system (predominantly visual feedback). They suggested that these two types of voluntary movements usually interact (moving towards a pen on a table requires movement in intrapersonal and extrapersonal space); however, since the information required for each type of movement is different, they proposed that cerebral organization for these movements might also differ. Experimental evidence supporting this theory noted increased regional cerebral blood flow (rCBF) in the posterior parietal cortex during voluntary movements in extrapersonal space (touching specific squares in a maze and making spirals in the air) and increased rCBF in the bilateral supplementary motor areas and the contralateral primary motor cortex during movement programming and execution in intrapersonal space (pressing a spring-loaded cylinder between thumb and index finger or touching the thumb to each finger in quick succession). These findings suggest distinct systems responsible for coding the space occupied by the body (intrapersonal space) and the space beyond the body (extrapersonal space).

Rizzolatti, Gentilucci, and Matelli (1985), and Rizzolatti and Camardi (1987) have acknowledged the distinctions noted above (far from body vs near body observed by Brain, 1941; and near body vs on/within body observed by Roland, Skinhoj, Lassen, and Larsen, 1980) to describe three discrete spatial regions: far space (beyond the reach of the body), peripersonal space (within the reach of the body), and personal space (on or within the body).

Personal space as defined by Rizzolatti et al (1985, 1987) is equivalent to the region labelled 'intrapersonal space' by Roland, Skinhoj, Lassen, and Larsen (1980). This area is associated with oral and tactile experiences and encompasses any stimuli located on the body.

Peripersonal space as defined by Rizzolatti et al (1985, 1987) is equivalent to the region labelled 'extrapersonal space' by Roland et al (1980) and the area labelled 'grasping space' by Brain (1941). This area is regulated by reach capabilities and encompasses any stimuli located within the reach of the body. Previc (1990, 1993a, 1993b, 1998) also referred to peripersonal space in his discussion of spatial coding. However, in contrast to Rizzolatti et al (1985, 1987), Previc did not distinguish between space occupied by the body (personal) and space immediately around the body (peripersonal). Previc (1990, 1993a, 1993b, 1998) defined peripersonal space as the area both containing and immediately surrounding the body (expanding 30 degrees laterally to each side of the midline) and suggested that this region is associated with visual grasping/manipulation and consumption. Previc (1990, 1993a, 1993b, 1998) argued that attention in this area is biased towards the lower visual field, as this constitutes the main area of reaching space. Research exploring spatial coding in relation to the body has proposed that it may be appropriate to further subdivide peripersonal space. Ladavas and Farne (2004) argue that studies investigating visuo-tactile extinction for stimuli located around the face and hands suggest that peripersonal space should be further sectioned into near peripersonal and far peripersonal: near peripersonal space is within 7cm from the body part and far peripersonal space is beyond 35cm from the body part. They found that patients demonstrating a failure to detect contralesional tactile stimuli during the presence of concurrent ipsilesional visual stimuli have been found to dissociate between visual stimuli located within 7cm of the body and visual stimuli located beyond 35cm from the body. Ladavas and Farne (2004) concluded that extinction can occur as a result of stimuli presented in near peripersonal space but does not usually occur as a result of stimuli presented in far peripersonal space.

Far space as defined by Rizzolatti et al (1985, 1987) is equivalent to the walking space proposed by Brain (1941). This region is related to oculor-motor capabilities and encompasses any stimuli located beyond reach yet within view of the body.

Previc (1990, 1993a, 1993b, 1998) expanded on the distinctions proposed by Rizzolatti et al (1985, 1987) by redefining far space as extrapersonal space and further dividing this region into focal, ambient, and action extrapersonal space.

Focal extrapersonal space refers to an American football shaped area located beyond peripersonal space expanding 20-30 degrees laterally and focused at fixation. Previc (1998) argues that the primary function of processing in focal extrapersonal space is visual search and recognition of external stimuli, and there appears to be a bias in visual attention towards the upper field of focal extrapersonal space as this constitutes the main area of object recognition space (Previc, 1996).

Ambient extrapersonal space refers to a large area beyond peripersonal space expanding 180 degrees laterally and consisting of the most eccentric and distant areas of the visual field. Previc (1998) suggests that this region is associated with spatial orientation, locomotion, and postural control, and visual attention appears to be biased towards the lower field of ambient extrapersonal space as this constitutes the main area of body space (Telford & Frost, 1993).

Action extrapersonal space refers to a large area beyond peripersonal space expanding the full 360 degrees around the body. Previc (1998) proposes that processing in this region involves activating memory, attention, and voluntary motor systems for navigation and orientation through a scene. There appears to be a bias towards the upper field of action extrapersonal space for both visual attention (Previc & Intraub, 1997, found that 3D visual memory is biased towards the upper field) and auditory attention (Barfield, Cohen, & Rosenberg, 1997, found that auditory localisations are biased towards the upper field).

Research investigating responses to stimuli located in personal, peripersonal, and extrapersonal space has suggested that there may be distinct neural circuits responsible for coding stimuli located on the body, within reaching distance of the body, and beyond the reach of the body.

Based on their spatial definitions, Rizzolatti et al (1985, 1987) argued that space occupied by the body (personal space) and located near to the body (peripersonal space) is associated with cortical activation in the motor regions (Brodmann areas 6 and 4) and somatosensory regions (7a and 7b), whereas space located far from the body (extrapersonal space) is associated with the frontal eye fields (8), the posterior parietal cortex (7b), and the superior colliculus.

Previc (1990, 1993a, 1993b, 1998) has proposed similar neural correlates on the basis of his definitions of peripersonal and extrapersonal space. Previc (1990, 1993a, 1993b, 1998) argued that peripersonal space is associated with cortical activation in the inferior parietal, dorsal postarcuate frontal, and posterior cingulate cortex, and subcortical activation in the cerebellum, globus pallidus, and putamen. He suggested that the dorsolateral visual pathway feeds this region (e.g.. DeYoe & Van Essen, 1988; Felleman and Van Essen, 1991; Maunsell & Newsome, 1987; Merigan & Maunsell, 1993). Previc (1990, 1993a, 1993b, 1998) further identified distinct neurological areas associated with each of his three subdivisions of extrapersonal space. Focal extrapersonal space is fed by the ventrolateral visual pathway (e.g., DeYoe & Van Essen, 1988; Felleman and Van Essen, 1991; Maunsell & Newsome, 1987; Merigan & Maunsell, 1993) and associated with cortical activation in the inferotemporal, arcuate frontal, and lateral intraparietal cortex, and subcortical activation in the superior colliculus, caudate nucleus, and lateral pulvinar. Ambient extrapersonal space is fed by the dorsomedial visual pathway (e.g., Gattass, Rosa, Souza, Pinon, Fiorani, & Neuenschwander, 1990; Nascimento-Silva, Gattass, Fiorani, & Souza, 1995) and associated with cortical activation in the parietaloccipital, retroinsular, and possibly the dorsal frontal cortex, and subcortical activation in the ventroposterior thalamus, vestibular nuclei, cerebellum, and putamen. Action extrapersonal space is fed by the ventromedial visual pathway (e.g., Martin-Elkins & Horel, 1992; Felleman & Van Essen, 1991; Saleem & Tanaka, 1996) and associated with cortical activation in the superior temporal, medial temporal, posterior cingulate, and ventromedial frontal cortex, and subcortical activation in the superior colliculus and anterior thalamus.

Research exploring the role of the motor regions in the coding of personal and peripersonal space has implicated the premotor and supplementary motor cortex (Brodmann area 6) and the primary motor cortex (4). Graziano and Gross (1998) reviewed studies investigating neurons in the ventral premotor cortex responsible for coding the space immediately surrounding the face, arms, and upper torso. They concluded that many of these neurons respond to both tactile and visual (or, in some cases, auditory) stimuli and these bimodal neurons have a receptive field associated with a specific body part. This receptive field remains linked to the body part despite movement of the eyes (Graziano & Gross, 1995) and shifts with the body part in a manner which suggests that space is encoded in body-part-centred coordinates, rather than eye-centred coordinates (Graziano, Hu, & Gross, 1997). Visual or auditory stimuli located close to the body part were found to elicit firing whereas stimuli located further from the body part did not result in a neural response. For example, neurons linked to the back of the head would respond to auditory stimuli originating from within approximately half a meter from the head, but would not fire in response to stimuli located further away (Graziano, Jin, & Gross, 1997). These body-part-centred coordinates suggest the existence of spatial maps at a neural level and these maps may assist in guiding movement in relation to external stimuli. Fogassi, Gallese, Fadiga, Luppino, Matelli, and Rizzolatti (1996) have proposed further evidence to suggest that the motor regions are responsible for coding near space. They noted that neurons in the caudal part of the inferior region of the postarcuate frontal area of conscious monkeys consisted of both unimodal and bimodal cells responsible for coding visual and somatosensory information. These neurons were found to fire in response to light tactile stimulation of the skin and visual stimuli located near the body, especially moving stimuli approaching the body. Rizzolatti, Matelli, and Pavesi (1983) further investigated the role of this area in spatial coding to observe visual neglect of peripersonal contralesional hemispace following unilateral lesions to the postarcuate frontal area. Similar research also noted visual neglect of distant contralesional hemispace following unilateral lesions to the frontal eye fields and visual neglect (Rizzolatti et al, 1983)

Alternative research investigating the neural circuits responsible for spatial coding has implicated the intraparietal sulcus and the arcuate sulcus. Colby, Duhamel, and Goldberg (1993) and Duhamel, Colby, and Goldberg (1998) found that unimodal (visual only) and bimodal (visual and tactile) neurons in the ventral intraparietal sulcus of the macaque monkey would fire in response to visual stimuli presented near to the face (within 20cm). They concluded that the ventral intraparietal area is responsible for constructing a representation of near head space. Similarly, Rizzolatti, Scandolara, Matelli, and Gentilucci (1981) investigated the activation of neurons in the periarcuate cortex of the macaque monkey. They found that unimodal neurons located rostral to the arcuate sulcus were activated by visual stimuli presented far from the body whereas bimodal neurons located caudal to the arcuate sulcus were activated by tactile stimuli on the body and visual stimuli presented near to the body. In addition, these bimodal neurons could be further categorised as pericutaneous (these neurons will activate in response to tactile stimuli or visual stimuli presented less than a few cm from the body) or distant peripersonal neurons (these neurons will activate in response to visual stimuli presented within reaching distance). This finding would support the suggestion presented by Ladavas and Farne (2004) that peripersonal space should be subdivided into near and far peripersonal space.

Rizzolatti et al (1985, 1987), Previc (1990, 1993a, 1993b, 1998), and Ladavas and Farne (2004) each describe valid spatial boundaries, and the evidence does seem to suggest a neural correlate between these regions of space and specific areas of the brain. Previc (1990, 1993a, 1993b, 1998) presents a thorough division of extrapersonal space - particularly relevant for research exploring the negotiation of movement through the environment – yet he fails to acknowledge the distinction between space occupied by the body and space directly surrounding the body. This distinction was, however, noted by Rizzolatti et al (1985, 1987) in his discussion of personal and peripersonal space. Ladavas and Farne (2004) expand on the concept of peripersonal space by dividing the area into space located close to the body and space located further from the body. Perhaps a complete division of spatial regions should refer to personal, near peripersonal, far peripersonal, focal extrapersonal, ambient extrapersonal, and action extrapersonal space in order to account for all of the relevant research findings.

For the purposes of the current thesis, however, divisions of space will be restricted to personal, peripersonal, and extrapersonal. Although the value of more detailed divisions of extrapersonal and peripersonal space is appreciated, it is not deemed necessary for the experiments completed in this thesis. Personal space will be defined as 'on body' space (within or on the body); peripersonal space will be defined as 'near body' space (within the reach of the stationary body); and extrapersonal space will be defined as 'far body' space (beyond the reach of the stationary body). Evidence for these spatial distinctions - particularly distinctions between stimuli located within the reach of the body (peripersonal or near space) and stimuli located beyond the reach of the stationary body (extrapersonal or far space) – has been presented in various areas of psychology, including clinical, cognitive, and neurological fields of research.

Space: Dissociation between Peripersonal and Extrapersonal Space

Clinical research has noted distinctions between peripersonal and extrapersonal space in studies of visuo-spatial neglect. Patients failing to attend to the contralesional side of space following lesions to the right hemisphere have been found to dissociate between stimuli located near the body (peripersonal space, in accordance with the definitions outlined previously) and far from the body (extrapersonal space) (Rizzolatti, Matelli, & Pavesi, 1983). Halligan and Marshall (1991) investigated a patient with left sided hemiparesis and visuo-spatial neglect following a unilateral right hemisphere cerebrovascular accident. They found that the patient demonstrated neglect for stimuli located in left peripersonal space whereas neglect was reduced or abolished for stimuli located in left extrapersonal space. Conversely, Cowey, Small, and Ellis (1994) found that patients demonstrating neglect for left-sided stimuli showed significantly worse performance on a line-bisection task presented in extrapersonal space relative to peripersonal space. Patients typically displaced the centre of a line slightly to the right during line bisection tasks completed with an ink pen, but they displaced the centre of the line significantly more to the right during line bisection tasks completed with a projection light pen.

Similar research by Coslett, Schwartz, Goldberg, Haas, and Perkins (1993) has also noted improved performance in motor and sensory tasks completed in peripersonal space, as opposed to extrapersonal space, in a patient with damage to the left temporo-parietal and left anterior cingulate regions. Further investigation by Cowey, Small, and Ellis (1999) replicated the results of Cowey Small and Ellis (1994), in addition to expanding on these findings by suggesting that there is not a distinct boundary between peripersonal and extrapersonal space. They studied line bisection performance in thirteen patients demonstrating left visuospatial hemineglect following a right hemisphere stroke. Performance was found to be significantly worse in line bisection tasks located further from the body in five of the thirteen patients. Furthermore, these findings indicated a gradual change from peripersonal space to extrapersonal space, rather than an abrupt distinction between the two areas. They did not find that displacement suddenly increased at the point just beyond maximum reach distance, but rather that errors increased gradually as the task was moved further into extrapersonal space. These experiments highlight the distinction between peripersonal space and extrapersonal space and support the suggestion that there are neurologically distinct, although possibly related, regions responsible for coding stimuli located close to the body and far from the body.

Pseudo-neglect observed in neurologically normal participants has also provided evidence to suggest a dissociation between near (peripersonal) and far (extrapersonal) space. Bjoertomt, Cowey, and Walsh (2002) investigated the effect of transcranial magnetic stimulation on performance in forced-choice length estimate tasks. Participants were presented with a transected line in near space (50cm from the face) or far space (150cm from the face) and were required to state whether the left side or right side of the transection appeared longer. Error analysis revealed that the estimates were more accurate in extrapersonal space relative to peripersonal space. They found that midpoint estimates were displaced in peripersonal space tasks during neural stimulation of the right posterior parietal cortex and in extrapersonal space tasks during neural stimulation of the right ventral occipital lobe.

Further investigation of line bisection performance in neurologically intact participants has been conducted by Weiss, Marshall, Wunderlich, Tellman, Halligan, Freund, Zilles, and Fink (2000). They measured regional cerebral blood flow using PET during pointing and line bisection tasks in twelve normal participants. Line bisection completed with an ink pen and pointing to dots in peripersonal space resulted in left hemisphere neural activation in the thalamus, ventral premotor cortex, intraparietal cortex, and dorsal occipital cortex. In contrast, line bisection completed with a laser pen and pointing to dots in extrapersonal space resulted in bilateral hemisphere neural activation in the ventral occipital cortex and right hemisphere neural activation in the medial temporal cortex.

Spatial distinctions between peripersonal and extrapersonal regions have also been observed in studies of visuo-tactile extinction. Patients demonstrating a failure to detect contralesional tactile stimuli during the presence of concurrent ipsilesional visual stimuli have been found to dissociate between visual stimuli located close to the body and visual stimuli located far from the body. Ladavas, di Pellegrino, Farne, and Zeloni (1998) investigated patients suffering tactile extinction following right hemisphere damage. They observed inhibited processing of tactile stimuli on the contralesional hand during visual stimulation close to the ipsilesional hand and noted that this extinction was reduced when the visual stimuli was presented further from the ipsilesional hand (beyond peripersonal space). Additional investigation has discounted the possibility that the body part acts as a cue to direct attention towards the visual target in these studies. Di Pellegrino and Frassinetti (2000) found enhanced detection of contralesional visual stimuli when the patient positioned his left hand close to the location of the visual target and revealed that this effect did not occur in response to an equivalent size object located close to the target. This finding suggests that there is enhanced processing for stimuli located in the space around the hand.

Similar spatial distinctions have been associated with stimuli located close to body parts other than the hands. Ladavas, Zeloni, and Farne (1998) observed enhanced extinction for tactile stimuli delivered to the contralesional side of the face during the concurrent presentation of visual stimuli near the ipsilesional side of the face and noted that extinction was significantly reduced when visual stimuli were presented far from the face. This finding suggests that the distinction between peripersonal and extrapersonal space is not restricted to the area around the limbs, but rather encompasses the body as a whole.

Further research has attempted to establish the relative roles of top-down and bottom-up processing in the extinction phenomenon. Ladavas and Farne (2004) investigated a patient demonstrating reduced contralesional tactile detection during bilateral cross-modal tactile-visual stimulation. They found reduced detection of left tactile stimuli during the presentation of visual stimuli near the right hand. They did not find any evidence of reduced contralesional tactile detection when the visual stimuli were presented far from the right hand. These findings highlight the distinction between near-body-space and far-body-space. Additional experiments by Ladavas and Farne (2004) then attempted to establish whether the construction of these spatial regions is mediated by a 'cognitive' top down process (distinguishing between near and far stimuli in terms of whether the item could potentially touch the body). Participants were prevented from judging the 'near' visual stimuli as an object that could possibly touch their body by covering the hand with a plexiglass shield. Ladavas and Farne (2004) found that the presence of the shield had no effect on the reduced detection of left tactile stimuli during the presentation of visual stimuli near the right hand. These findings suggest that the spatial mapping of peripersonal and extrapersonal regions is not influenced by top-down regulation of sensory processing, but rather it is an automatic process directed in accordance with a bottom-up flow of information about the location of the body in space. These findings have been supported in related research exploring responses to occluded visual stimuli in a cross-modal distracter congruency task (Kitagawa & Spence, 2005; see below).

Spence, Pavani, and Driver (1998, 2004) developed the cross-modal distracter congruency task to demonstrate that normal participants are significantly worse at detecting vibrotactile stimulation of the finger or thumb during the presence of incongruent visual distracters located near the finger or thumb. These visuo-tactile congruency effects are more pronounced when the visual stimuli is presented near the stimulated hand, as opposed to far from the stimulated hand. Further research has revealed that this effect remains whether the hands are in a crossed or uncrossed position, and Spence et al (2004) note that this finding highlights the adaptable nature of the anatomical mapping between the senses to allow for repeated changes in our posture throughout daily life. Cross-modal congruency effects further demonstrate the distinction between peripersonal space and extrapersonal space for each specific limb. Furthermore, as referenced above with regards to top-down and bottom-up processing, Katagawa and Spence (2005) found that this mapping of body space is not mediated by a conscious awareness of whether the hand can be touched by the visual stimuli as the visuo-tactile congruency effect remains despite the presence of a transparent barrier between the vibrotactile targets on the hand and the visual targets near the hand.

Space: Dissociation between Personal and Peripersonal Space

Hari and Jousmaki (1996) were among the first to illustrate the dissociation between personal space and peripersonal space. They found that motor activity is initiated more efficiently in response to stimuli located on the responding limb (personal space), as opposed to near the responding limb (peripersonal space). Subsequent research adopting the method used by Hari and Jousmaki (1996) suggested that there is an attention bias towards stimuli located on the body (Whiteley, Kennett, Taylor-Clarke, and Haggard, 2004). These studies highlight the distinction between spatial coding for stimuli located in personal space and spatial coding for stimuli located in peripersonal space. Both of these studies are critical to the current thesis so they shall be discussed in more detail in Chapter 3 prior to the introduction of the first experiment of the thesis.

There has been considerably less evidence to support this distinction between personal (space occupied by the body) and peripersonal space (space close to the body) than there has been to define the boundaries between peripersonal and extrapersonal space. It is, however, important for research to explore this division because this distinction is crucial to our comprehension of how the brain understands the difference between the body and the surrounding environment.

Schema: Mental Representation of the Body

The concept of the body schema has emerged from research investigating the understanding of the body in the brain. Neurological evidence suggests that the physical body is represented in the brain on numerous levels. Somatosensory and motor representations of the body can be observed in the somatotopic organisation of the sensory and motor cortex, and the homunculus proposed by Penfield and Rasmussen (1950) illustrates how the body is mapped in the brain. The concept of the body schema, however, refers to a more comprehensive and all-encompassing representation of the physical body in the brain.

Head and Holmes (1911) are frequently cited as the first to propose the term 'body schema' in reference to an internal representation of the physical body. They distinguished between the postural body schema and the superficial body schema. The postural schema represents the position of the body whereas the superficial schema represents the skin of the body. Current research in this field tends to focus on the concept of the postural body schema; although it is worth noting that the superficial or surface body schema may be more relevant for research investigating responses to stimuli located on the body.

More recent discussions of neural representations of the body have offered a wider definition for the concept of the body schema. Berlucchi and Aglioti (1997) define the body schema as a 'mental construct that comprises the sense impressions, perceptions, and ideas about the dynamic organisation of one's own body" (Berlucchi & Aglioti, 1997, p. 560). Schilder (1935/50) further clarified this concept to refer to an internal representation or image of the body. Interestingly, Berlucchi and Aglioti (1997) expand on their definition to argue that the body schema also allows an individual to understand the physical composition, position, and location of bodies other than their own.

Graziano and Botvinick (2002) propose an alternative, yet related, definition for the body schema. They describe this concept as an 'implicit knowledge structure that encodes the body's form, constraints on how the body's parts can be configured, and consequences of the configuration on touch, vision, and movement" (Graziano & Botvinick, 2002, p. 145). They note that the body schema is an integrated model drawing information from various sources including vision, proprioception, sensation, and motor activity, and they suggest that Brodmann area 5 may be implicated in the formation of a cohesive body schema as this region receives input from areas associated with all of these processes. Evidence to highlight the role of area 5 in the production of a comprehensive body schema has been presented throughout the field of neuropsychology. Murray and Mishkin (1984) argued that area 5 is associated with proprioceptive feedback as it appears to be responsible for processing information related to the felt position of a limb and this proposal was supported by Rushworth, Nixon, and Passingham (1997a,b) who found that this area is crucial for guiding arm movements in the absence of visual feedback. Mountcastle, Lynch, Georgopoulos, Sakata, and Acuna (1975) suggested that area 5 is associated with motor feedback as neurons in this region often only respond during active, rather than passive, movements of the limb and this proposal was further supported by Seal, Gross and Bioulac (1982) who noted that activity in this region could not be the result of proprioceptive feedback alone since neurons in this area responded before and during movements even after the sensory nerves had been severed. Graziano, Cooke, and Taylor (2000) proposed that area 5 is responsible for coding both the seen and felt position of the limbs as they found that neurons in this region were sensitive to the seen position of a realistic false arm located as though it were protruding from the shoulder in an anatomically correct manner. All of these findings suggest that this region is associated with both moving and appreciating the movement of the body, and these processes are generally assumed to form the basis of a comprehensive body schema. For this reason, it was proposed by Graziano and Botvinick (2002) that the neural basis of the body schema is likely to lie in Brodmann area 5.

Schema: Nature vs Nurture

There is an ongoing debate within psychology and philosophy as to the relative input of nature and nurture on the creation of the body schema. Traditional approaches in this field assumed that the body schema was created through experience and this theory was supported by evidence to suggest that infants did not appear to hold a complete body schema. Piaget (1962) suggested that children under the age of eight months are unable to imitate the facial expressions of others because they do not have an intact schema for representing movement in their own face. Subsequent research, however, found that this assumption might be inaccurate since there may exist an innate basic framework for the body schema available for further development through the process of experience. Meltzoff and Moore (1983, 1989, 1977, 1994) have found that infants as young as one hour old can imitate the facial expressions of adults under certain conditions. This finding suggests that the infant is able to convert visual information relating to the face of the adult to motor activity in the face of the baby and this ability requires that the infant is able to incorporate visual and proprioceptive systems. It is proposed that these systems form the basis of the body schema: an understanding of how to manipulate the facial muscles to reproduce a seen expression indicates an intact representation of the body on a basic level.

An innate basis for the body schema would suggest that the representation of the body is usually fixed and constant, and this would appear logical as the body itself does not often change in a dramatic manner. Indeed, sudden changes to the body can result in some unusual consequences with regards to the body schema. Graziano and Botvinick (2002) suggest that many perceptual illusions arise from the fixed nature of the body schema. For instance, Benedetti (1988) noted that participants can misjudge the size of an object as a result of tactile exploration of the object with the hand in an unusual position, such as crossed fingers. Graziano and Botvinick (2002) suggested that this illusion is due to the brain failing to represent the body in the new, unusual, position. It is interesting to note, however, that Benedetti (1988) found that this illusion does fade if the participant is given time to adjust to the new position, suggesting that the body schema is capable of alteration under certain conditions.

Further research exploring the nature/nurture debate with regards to body schema has investigated the experience of phantom limbs. Phantom limb syndrome was first proposed by Mitchell (1871) as the experience of an amputated limb as though it were still a part of the body. Ramachandran and Hirstein (1998) note that approximately 90-98% of all amputee patients experience a phantom and this experience will often involve cramping or pain. Most phantoms are limbs, but reports have also noted phantoms for other external (for example, sensation in the breast after a mastectomy) and internal (for example, menstrual cramps after an hysterectomy) parts of the body. Phantoms will most commonly appear immediately after the amputation and usually last for several days or weeks, although some phantoms can persist for several years.

Numerous explanations have been proposed to explain the existence of phantom limbs. Many of these accounts have suggested that a body schema established through the process of experience will take time to adapt to subsequent dramatic changes to the physical body and phantom limbs will be experienced during this transitional phase as the schema changes from the representation of the previous body to the representation of the new body. This theory has received some support in the literature. In particular, evidence shows that a phantom limb is not experienced by those patients who progressively lose a limb due to a disease such as leprosy (Simmel, 1956) and this finding suggests that in these cases the body schema has time to adjust to physical changes through the process of experience. Furthermore, evidence has been presented to suggest that amputation of a surgically altered limb can lead to the experience of an equivalently shaped phantom. For example, Kallio (1949) notes that upper limb amputee patients may have their stump shaped into a fork in order to make the appendage more useful (a fork can be used as a pincer to grasp objects) and subsequent amputation of this forked stump can result in a fork-shaped phantom limb. This finding suggests that the body schema has gradually changed to accept the new shape of the limb, but the sudden loss of this new limb will result in an equivalently shaped phantom until the schema has readjusted to the new body shape. These explanations for phantom limbs imply that the development of the body schema occurs as a result of experience of the physical body (nurture).

Weinstein and Sersen (1961), however, observed that 17% of aplasic patients (congenital absence of a limb) have also experienced a phantom limb suggesting that there may be an innate basis for the body schema (nature). Early discussion of congenital phantoms noted that these sensations usually develop relatively late in life (often between the ages of five and eight years, Gallagher and Meltzoff, 1996); therefore it could be argued that the congenital phantom is simply a delusion resulting from the desire to be 'normal' once the child has grown to understand that their own body is different. One case study described by Ramachandran (1993b), however, discounts this possibility as the congenital phantom experienced by his patient was considerably shorter than normal limbs and did not move in a normal manner, thus it was unlikely that the existence of a congenital phantom in this case was simply a form of wish fulfilment. This finding suggests that the experience of the congenital phantom is essentially similar to the experience of phantoms reported by amputee patients and both of these types of phantoms are examples of a body illusion, rather than a delusion resulting from a desire to be normal (Ramachandran & Hirstein, 1998). Congenital phantoms may, therefore, be taken as evidence for an innate body schema as an aplasic patient will not have had an opportunity to develop a body schema through the process of experience.

Current explanations for invisible imitation, body-related perceptual illusions, and phantom limbs tend to adopt an eclectic approach highlighting the importance of both nature and nurture on the development of the body schema. Melzack (1990) proposes a genetically determined 'neuromatrix' responsible for outlining a basic body schema available for subsequent manipulation through sensory experience. Gallagher and Meltzoff (1996) suggest that this innate framework of the body schema will undergo modification and alteration as a result of experience throughout the life of the individual. This proposal is supported by Berlucchi and Aglioti (1997) who noted that the body schema must demonstrate both stability and plasticity in order for it to accept normal gradual changes in the physical body (such as changes in height and weight). This thesis will consider the flexibility of the body schema in more detail in Chapter 2.

Schema: Difficulties in Operationalisation

The concept of the body schema has been subject to some criticism in recent reviews of the literature. Maravita, Spence, and Driver (2003) suggest that this concept should be invoked as a label for a set of problems, rather than an explanation for behaviour, since it fails to offer any actual rationalization as to how an internal representation can mediate responses to external stimuli. Similarly, Holmes and Spence (2006) note that the concept of the body schema is too wide to offer an adequate explanation for all of the associated behaviours and they propose that research should focus on specific aspects of representation in order to explore how the body is understood in the brain.

It is important to note that the notion of the body schema should remain conceptually distinct from the concept of body image and, as noted by Gallagher and Meltzoff (1996), this distinction often fails to be acknowledged in the current literature. Schilder (1935/50) used the term 'body schema' interchangeably with the term 'body image', yet Gallagher and Meltzoff (1996) note that these two expressions may relate to entirely different understandings of the body. They argue that the body image refers to a perception of or belief about the body whereas the body schema refers to an understanding about the physical capabilities of the body. This is an interesting distinction as it suggests that the body image contains information relating to the perceptual experience of the body, conceptual knowledge of bodies in general, and emotional attitude with regards to the body. Body schema, on the other hand, is quite specifically responsible for information relating to the motor capabilities of the body.

It is clear that the original concept of the body schema (Head & Holmes, 1911) has undergone considerable transformation over the years (for review see Holmes & Spence, 2006) and it is currently applied to describe a wide variety of body-related psychological phenomenon. For the purposes of the current research, the concept of the body schema will initially be defined as an internal representation of the body, in accordance with the traditional view of the literature. Research completed within this thesis, however, will explore the concept of the body schema with the aim of clarifying this definition with particular focus on the idea of the body schema as a representation of the motor capabilities of the body (as proposed by Gallagher & Meltzoff, 1996).

Space and Schema

Body schema, as it is currently defined in the literature, can be closely related to the concept of personal space. Current descriptions define body schema as a general internal representation of the body. In contrast, personal space can be defined as the area of external space occupied by the body. In essence, body schema refers to the component parts of the physical body (what we are) whereas personal space refers to the spatial location of the physical body (where we are) and the combination of these two concepts can establish a sense of self (who we are). The terms 'body schema' and 'personal space' do, therefore, appear to refer to distinct, albeit related, concepts. Unfortunately, the literature in this area often fails to acknowledge this distinction to the extent that the terms are used interchangeably. This does not usually constitute a problem for the research: for example, it was earlier concluded that Hari and Jousmaki (1996) highlighted the distinction between personal space and peripersonal space, although one might equally have described these findings as highlighting the distinction between stimuli associated with the body schema and stimuli not associated with the body schema. Failure to clarify these terms does, however, blur the boundaries between the two concepts so that they become confusing and misleading. For the purposes of the current thesis, theoretical discussion will refer to both personal space AND body schema - rather than using the two terms interchangeably - in order to ensure that the reader remains aware that these two concepts are distinct. In those cases when it is inappropriate to refer to one of these concepts (if, for instance, the body schema will remain fixed but personal space may be manipulated, or vice versa), the text will be clear about which concept is under investigation.

Chapter 2

Flexibility of Space and Schema

Chapter 1 highlighted the various distinctions in spatial coding and, in particular, demonstrated the differences in responses to stimuli located close to the body and far from the body. Further review of research in this area, however, suggests that this spatial coding may be flexible to the extent that objects located some distance from the body can be re-coded as though they are located close to the body and objects located close to the body can be re-coded as though they are located some distance from the body. Chapter 1 also reviewed the concept of the body schema and proposed the existence of a fixed mental representation of the physical body. Further examination of the research in this area, however, suggests that this body schema may actually be flexible enough to allow manipulation under certain circumstances. There have been five main areas of groundbreaking research which support the theory that spatial coding of regions around the body and the body schema can be flexible: Tool Research, Phantom Hand Research, Rubber Hand Research, Clothing Research, and Limb Projection Research.

Tool Research

Plasticity of spatial coding is demonstrated in experiments showing that peripersonal and extrapersonal space can be modified in accordance with the physical capabilities of the body. Iriki, Tanaka, and Iwamura (1996) suggest that peripersonal space can be extended as a result of the incorporation of a distinct external object into the body schema. They identified bimodal neurons responsible for coding the hand schema in the caudal postcentral gyrus of the macaque monkey. These neurons were found to fire in response to stimuli located close to the hand. Experimental research revealed that the visual receptive field of these neurons could be modified by the use of a hand held rake to the extent that the neurons would begin to fire in response to stimuli located close to the tool. This effect was dependent on active use of the tool, and, as such, would begin to fade quickly after the tool was removed or even unused by the monkey for a period of time. Iriki et al (1996) concluded that the rake had been incorporated into the hand schema and peripersonal space had been extended along the length of the tool. These conclusions have, however, been criticised by Holmes and Spence (2004) in an evaluative review of several issues relating to the design and interpretation of the findings of this study, including failure to control for potentially confounding visual fixation, attention, response preparation, and body movement effects. They note that the region of interest under investigation in this study contains a minimum of five functionally distinct sub-regions and research has identified many different properties of the neurons located within this area (Mountcastle, Lynch, Georgopaulos, Sakata, & Acuna, 1975), thus it is difficult to attribute the findings of this research to a specific bias towards stimuli located in peripersonal space without controlling for all possible confounding variables.

Behavioural research has, however, also indicated flexibility of spatial coding following tool use. Maravita, Spence, Kennett, and Driver (2002) investigated effects of tool use in a visuo-tactile interference paradigm. It has been noted that participants demonstrate increased reaction times and errors for detecting tactile stimulation of a finger or thumb during the appearance of an incongruent visual distracter near the stimulated hand (Pavani, Spence, & Driver, 2000). Maravita et al (2002) found that visual distracters located near the end of a tool held by the stimulated hand could have a similar effect on responses: visual targets at the end of the tool located in the opposite upper or lower position to the tactile stimulation would result in increased reaction times and errors. They revealed that this effect remained even when the tools were crossed so that visual distracters were located at the end of the tool in the opposite hemispace to tactile stimulation. It was observed that this effect was dependent upon active tool use and increased in accordance with tool experience. Further research exploring visuo-tactile interference has revealed that the use of tools does not lead to an 'extension' of peripersonal space, but rather a 'projection' of peripersonal space (Holmes, Calvert, & Spence, 2004). Holmes et al (2004) measured responses to upper or lower elevation vibrotactile stimulation to the hands during the concurrent presentation of upper or lower visual stimuli located near the handle, shaft, or tip of a hand-held tool. They identified a cross-modal congruency effect for visual distracters presented near the handles and the tips of the tools following active tool use requiring the tip of the tool to be used to complete a task. They did not identify a cross-modal congruency effect for visual distracters presented near the shaft of the tool. These findings suggest that peripersonal space had not been 'extended' along the length of the tool (since this would have produced a similar effect for visual distracters presented near any part of the tool, including the shaft), but rather that peripersonal space had been 'projected' to include the region of space around the tip of the tool. This is an extremely interesting finding as it proposes that peripersonal space is flexible to the extent that it can incorporate regions of extrapersonal space around a tool, but that this flexibility can be accomplished without incorporating all of the spatial area between the body and the external object. Further discussion of the flexibility of spatial mapping in this thesis shall refer to 'projection' rather than 'extension' of space in accordance with the conclusions drawn in the study by Holmes et al (2004).

Research in this area has predominantly focused on the effects of tool use by human patients suffering from neglect or extinction. Hemispatial neglect refers to a failure to respond to contralesional stimuli and evidence suggests that there is a dissociation between near and far space for spatial neglect (Rizzolatti, Matelli, & Pavesi, 1983; Halligan & Marshall, 1991; Cowey, Small, & Ellis, 1994). Berti and Frassinetti (2000) found that a neglect patient with an impaired mechanism for near space would demonstrate neglect for stimuli in far space when the task was completed with a stick. It was suggested that the task located in extrapersonal space had been recoded as though it were located in peripersonal space. Conversely, experimental evidence presented by Ackroyd, Riddoch, Humphreys, Nightingale, and Townsend (2002) revealed that a neglect patient with an impaired mechanism for far visual space only would demonstrate improved detection of targets located in far space during the use of a reach extension tool. It was concluded that the enhanced visual representation of near space had been projected to include far space through tool use. Similar research by Pegna, Petit, Caldara-Schnetzer, Khateb, Annoni, Sztajzel, and Landis (2001) found that left neglect of far space was recorded during the use of a stick to perform the line bisection task, although this neglect was not observed during the use of a laser pointer. This study emphasises the importance of the tool in such research, as it would appear that the stick performed the function of projecting personal space into extrapersonal space whereas the laser pointer was not capable of manipulating spatial coding.

Further research has investigated the effect of tool use on cross-modal extinction. Farne and Ladavas (2000) found increased cross-modal extinction around the edge of a hand held rake after the use of the rake to retrieve objects. Patients failed to detect tactile stimulation of the left hand during the appearance of concurrent visual stimuli near the right hand, although tactile detection rates were not influenced by visual stimuli located far from the right hand. Following five minutes use of a rake tool to retrieve distant objects, however, patients failed to detect left tactile stimulation during the appearance of concurrent visual targets far from the right hand if these targets appeared close to the end of the rake. They concluded that peripersonal space around the hand could be manipulated in accordance with the use of a tool. These findings were supported by Maravita, Husain, Clarke, and Driver (2001). Maravita et al (2001) revealed that this effect was not due to the long tool cueing the far target as the increased cross-modal extinction was eliminated by a small gap between the hand of the patient and the tool. They suggested that the far stimuli had been recoded as near stimuli because they had become 'reachable' by the hand through the use of a tool. Similar research investigating the influence of tools on cross-modal extinction has emphasised the importance of active tool use in order to make the far stimuli appear within the reach of the participant. In contrast to previous research, Maravita, Clarke, Husain, and Driver (2002) found that cross-modal extinction could actually be reduced by linking the contralesional and ipsilesional hemispace through the active use of a tool. They investigated a patient demonstrating reduced detection of left hand tactile stimulation during concurrent visual stimulation near the right hand. This patient was required to hold a tool in his left hand in order to manipulate objects in right hemispace. They found that 10-20 minutes of active tool use would result in 60-90 minutes of reduced extinction for left tactile stimuli during the presentation of concurrent visual stimuli located near the end of the tool in right hemispace. They concluded that an actively used tool crossing from left to right can eliminate competition between stimuli located on opposite sides of the body.

Additional evidence for the flexibility of spatial coding in accordance with tool use can be noted in distance perception. Witt, Proffitt, and Epstein (2005) note that tool use can influence the perceived distance of a target. Participants were found to verbally estimate targets as closer when a tool was used to reach the target. These estimates were not, however, influenced by simply holding the tool; participants had to actively use the tool to reach the object in far space in order for the perceived distance to be reduced. This study supports the research of Iriki, Tanaka, and Iwamura (1996) and Maravita, Husain, Clarke, and Driver (2001) by emphasising the importance of active tool use in order to manipulate spatial coding. Indeed, Ladavas

(2002) concludes that research in this area has demonstrated that visual spatial coding has numerous dynamic properties permitting considerable flexibility of space and schema in response to the use of a tool to act on distant objects.

Phantom Limb Research

Phantom limb syndrome appears to demonstrate the existence of a persistent body schema representing a complete physical body, despite the absence of a particular body part. Phantom limb research may, therefore, appear to provide evidence for the fixed nature of the internal representation of the body rather than indicating the potential flexibility of the body schema. However, neurological investigation of phantom limbs has also found considerable evidence to indicate potential plasticity with regards to spatial coding and body schema.

Although research exploring phantom limbs in aplasic and amputee patients has suggested that there may be an innate basic framework or 'neuromatrix' for the body schema (Melzack, 1990), evidence has also proposed that this mental representation of the body will undergo a degree of modification and alteration as a result of experience throughout the life of the individual (Gallagher & Meltzoff, 1996). Research to support this proposal has noted cases of adorned phantom limbs: patients may experience the sensation of the phantom wearing a wedding band or watch suggesting the body schema of the individual had previously adjusted to incorporate the item of jewellery prior to the amputation (Melzack, 1992; Ramachandran & Hirstein, 1998). Further support has noted the existence of telescopic phantom limbs: Weiss and Fishman (1996) observed that many upper body phantom limbs will shrink over time until the remaining phantom is simply a hand or even just some fingers and this alteration of the phantom over time suggests some degree of modification of the underlying body schema. Ramachandran and Hirstein (1998) report that patients experiencing telescopic phantom limbs are occasionally capable of extending the limb out from the body to assume the normal length of an arm (for example, the patient may feel as though they are reaching for a cup by extending their shrunken phantom out to normal length) and this suggests that the body schema has also altered with regards to the physical capabilities of the limb. These explanations for phantom limbs imply that the body schema can be manipulated as a result of experience of the physical body.

Ramachandran and Blakeslee (1998) attributed the experience of phantom limbs in amputee patients to neural plasticity in the somatosensory cortex. Regions of the sensory cortex responsible for the afflicted body part will inevitably suffer a loss of sensory input following amputation. Fibres from these areas may then begin to encroach into neighbouring regions of cortex and, as a result, stimulation of these fibres will occur whenever the neighbouring areas are activated. For example, fibres from the area of cortex responsible for the hand may branch into the neighbouring cortex responsible for the cheek after amputation of the limb, so that any subsequent stimulation to the cheek may be simultaneously experienced as sensation in a phantom limb. This theory highlights the flexibility of neural coding for personal space and the body schema, and this suggests that these representations are malleable entities capable of adaptation in accordance with changes to the physical body.

Rubber Hand Research

The 'rubber hand illusion' also suggests that spatial coding and body schema are flexible to the extent that an external object may be incorporated into the representation of the body. Early research investigating body ownership found that a plastic finger can be mistakenly accepted as a real finger under certain conditions (Tastevin, 1937, as cited in Pavani, Spence, and Driver, 2000). Similarly, more recent research has revealed that a rubber hand can be mistakenly accepted as a real limb following specific tactile and visual stimulation. Botvinick and Cohen (1998) found that synchronous stroking of an actual hand and a rubber hand could result in an illusory tactile sensation. Participants were seated with their left arm hidden from view behind a screen and presented with a life-size rubber hand on the table directly in front of them. They were instructed to watch the rubber hand while the experimenter administered synchronous light strokes to both the rubber hand and the actual hand. Participants were asked to describe their feelings about the rubber hand in a questionnaire and 42% of these subjective reports indicated an experience of sensation from the rubber hand rather than the actual hand. Participants were also asked to indicate the location of their left hand by pointing under the table with their right index finger and those participants who had reported the illusory sensation were found to displace the location of the actual hand towards the rubber hand. Botvinick and Cohen (1998) noted that eight out of ten participants had felt as though the rubber hand had actually become a part of their own body and they concluded that these participants had assumed 'ownership' of the rubber hand. Similar research conducted by Rorden, Heutink, Greenfield, and Robertson (1999) revealed that a patient with improved detection of tactile targets during concurrent visual exposure to the stimulation of the hand will demonstrate similar improvement in detection during concurrent visual exposure to stimulation of a fake hand. Furthermore, evidence presented by Ehrsson, Holmes, and Passingham (2005) suggests that assumed ownership over the rubber hand is not only due to visual dominance as they found that the rubber hand illusion can be elicited in the absence of visual information. Blindfolded participants were required to touch the rubber hand with their real left index finger while the experimenter mimicked this contact on their real right hand. Measurement of the illusion was conducted through verbal reports and location displacement of the real hand toward the fake hand, and this tactile experience was found to elicit a rubber hand illusion in twenty-five of the thirty-two participants. All of these studies suggest that the body schema can be altered to incorporate an artificial limb.

Subsequent research investigating the rubber hand illusion has identified some features necessary for the incorporation of the artificial limb into the body schema. There is evidence to suggest that this illusion may be dependent on the synchronicity of stimuli associated with the real hand and rubber hand as asynchronous stroking of the rubber hand and the actual hand significantly reduced or entirely eliminated the illusion (Botvinick & Cohen, 1998). This illusion may also be subject to the similarity in physical appearance and orientation between the real hand and rubber hand. Tsakiris and Haggard (2005) investigated perceptual drift of the physical hand towards the rubber hand following various manipulations of the rubber hand illusion. They found that the rubber hand illusion was significantly impaired in experiments adopting neutral objects (stick instead of a rubber hand), incongruent rubber hand identity (opposite handedness in the rubber hand to the physical hand: for example, stimulation of the left physical hand and right rubber hand), and incongruent rubber hand posture (rubber hand positioned at a different orientation to the physical hand). Further research investigating the effects of rubber hand appearance and orientation in this illusion has adopted the cross-modal interference paradigm. Pavani, Spence, and Driver (2000) noted that participants demonstrated increased reaction times and errors for detecting tactile stimulation of a finger or thumb during the appearance of incongruent visual distracters near the digit of a rubber hand. This effect was not, however, observed when the rubber hand was spatially misaligned with the physical hand. Austen, Soto-Faraco, Enns, and Kingstone (2004) further supported these findings by revealing that this congruency effect was dependent on postural compatibility (although they did also find that this effect remains despite the fact that the real hand and the fake hand do not look identical and this effect can remain even when the fake hand is hidden from view). Similarly, Farne, Pavani, Meneghello, and Ladavas (2000) noted that patients with right hemisphere damage demonstrate cross-modal visuo-tactile extinction for real hands and rubber hands spatially aligned with the real limbs. Misaligned rubber hands positioned in an implausible posture (fingers directed towards the real shoulder) did not elicit cross-modal visuo-tactile extinction. These studies highlight the importance of visual appearance of an external object for the incorporation of the object into the body schema.

In contrast to research suggesting that the rubber hand illusion is dependent on the presence of a realistic rubber hand, evidence presented by Ramachandran, Hirstein, and Rogers-Ramachandran (1998) and Armel and Ramachandran (2003) suggests that the representation of the body can be manipulated to incorporate even obviously non-body objects. This research has reported a rubber hand type illusion in response to synchronous stroking of a hidden real hand and a table. Participants reported feeling as though tactile sensation was arising from the table and skin conductance responses were found to indicate increased arousal when the table was 'harmed'. Armel and Ramachandran (2003) conclude that the body schema is an extremely malleable entity capable of assimilating a surprisingly large variety of external objects.

Further research has revealed that the importance of the visual appearance of the rubber hand may be dependent on whether the individual is able to exercise some degree of control over the fake limb. Azanon and Soto-Faraco (2007) explored the effect of the rubber hand illusion on temporal order judgements. Previous research has demonstrated that the accurate perception of stimulation delivered to the index fingers of each hand can be impaired by the crossing of the hands: participants would often make mistakes about which finger had been touched first if they were concurrently observing their own crossed limbs (Yamamoto & Kitazawa, 2001). Azanon and Soto-Faraco (2007) replicated this study with the crucial difference that the participants observed crossed or uncrossed rubber hands located directly over their own obscured hands. The participant was required to indicate which finger had been touched first by pressing the same-sided button located beneath their real index fingers. The buttons under the index fingers of the real hands were connected to the buttons fixed to the index fingers of the rubber hands so that any pressing action by a real hand resulted in a concurrent depression of a button under a rubber hand. Prior to the temporal order judgements, participants were encouraged to incorporate the rubber hands into their body schema through an active movement habituation stage: participants completed a button press in response to a light while observing a concurrent movement in the rubber hand. Previous research has produced the rubber hand illusion through the use of concurrent visual and tactile information in the form of light strokes applied to the hands. The current study, however, produced the rubber hand illusion by presenting the participant with concurrent movement in the real and rubber hands. Azanon and Soto-Faraco (2007) found that participants were less accurate in their temporal order judgements when their hands were crossed. However, this result was modulated by the visual information provided by the rubber hands: participants were more accurate when the rubber hands were uncrossed even if the real hands were crossed. Further experimental studies revealed that this visual modulation of the temporal order judgement did not occur if the participant had not been exposed to the prior active movement habituation stage. Azanon and Soto-Faraco (2007) concluded that the visual influence of body posture is dependent on the movement of the visible part of the body being linked to personal motor activity.

Research investigating the neurological basis of the rubber hand illusion has highlighted specific neural areas responsible for establishing ownership of a body part. Graziano, Cooke, and Taylor (2000) studied primate neural activity in response to the sight of a fake arm located above a hidden real arm. They found that neurons located in area 5 of the parietal lobe of the monkey brain responded to the position of the real arm and the position of a fake arm. These neurons did not, however, respond to an unrealistic or misaligned fake arm. Similar research has explored human neural activity in response to a rubber hand. Ehrsson, Spence, and Passingham (2004) revealed specific areas of neural activity during exposure to the rubber hand illusion: in particular, bilateral premotor activation was found to correlate with the strength of the perceived illusion. Further evidence by Ehrsson, Holmes, and Passingham (2005) suggests that activity in the premotor cortex and cerebellum is associated with the feeling of ownership over the rubber hand.

Clothing Research

It may be suggested that the body schema can naturally extend to incorporate those objects that are closely related to the body, such as clothing. Head and Holmes (1911) noted that 'anything, which participates in the conscious movement of our bodies, is added to the model of ourselves and becomes part of these schemata: a woman's power of localisation may extend to the feather in her hat' (Head & Holmes, 1911, p188). It is clear that clothing is crucial to the expression of individuality and it may be argued that our clothing and adornments can become as much a part of the self as the physical body. Certain people will wear specific clothes designed to reflect an aspect of their personality and other people may dress in particular garments because they feel as comfortable in those clothes as they do in their own skin. Holmes and Spence (2006) suggest that new clothes – and, in particular, shoes – will require both neural and skeletomuscular adaptation before these items can be accepted as comfortable attachments to the body. This suggestion could imply that clothes will gradually become incorporated into the body schema through the natural process of wearing the attire.

Limb Projection Research

Evidence suggests that personal space can be extended to incorporate projections of the body displaced through shadows, mirrors, and video images.

Flexibility of personal space in accordance with the body shadow has been explored by Pavani and Castiello (2003). They proposed that personal space can be extended along the length of a shadow under certain conditions. Ten adults performed a speeded discrimination task detecting tactile targets on the thumbs or index fingers during the presentation of congruent or incongruent visual distracters near the shadow of the hand. They found that visuo-tactile interference was significantly stronger when tactile stimulation was presented to the hand casting the shadow and control studies revealed that this finding was not the result of the shadow directing attention to the distracters. Pavani and Castiello (2003) further found that this effect was dependent on the shadow appearing as a realistic body shaped image. They did not find visuo-tactile interference associated with a hand casting an unrealistic shadow due to the presence of a misshapen glove. This experiment highlights a number of interesting findings. Firstly, these results may suggest that a genuine body shadow can project personal space beyond the physical constraints of the body to incorporate regions of extrapersonal space. Secondly, Holmes and Spence (2006) suggest that this observed shadow-associated binding may be an adaptive strategy to enhance responses to potential threats (objects approaching the shadow are likely to swiftly collide with the actual body). And thirdly, this effect appears to be dependent on the visual appearance of the body shadow as the responses did not demonstrate the same pattern of results when the participant donned a glove to produce a non-hand shaped shadow. This final finding appears to be at odds with the suggestion that the effect may be evidence of an adaptive strategy to warn of potential threats. There are many occasions when a shadow may appear misshapen or deformed (poor lighting, clothing, hairstyles, etc: consider the shadow of a woman wearing a large hat!) thus it would be evolutionary disadvantageous for responses to be inflexible with regard to the visual appearance of the body shadow. Theoretically, it may seem more logical for shadows to be linked to the body through motor control (a shadow is assumed to belong to the self when movement of the body results in concurrent movement of the shadow) rather than linking the shadow to the body part through visual similarity. Pavani and Castiello (2003) fail to consider this possibility in their study as they do not appear to provide the participant with an opportunity to move their real hand in order to observe concurrent movement in the shadow. It would be interesting to explore whether the effect noted in this study could be reinstated for an unrealistic shadow if the participant has prior experience of control over the movement of the shadow.

The potential projection of personal space into extrapersonal space to incorporate images of the body reflected in a mirror has been investigated by Maravita, Spence, Clarke, Husain, and Driver (2000). They examined near space cross-modal visuo-tactile extinction in a right hemisphere stroke patient during concurrent tactile stimulation of the contralesional hand and visual stimulation near the ipsilesional hand. They found that extinction also occurred in response to stimuli located near the mirror reflection of the ipsilesional hand, despite the fact that this reflection was located in far space. These findings have been supported in related non-patient research exploring cross-modal interactions following exposure to hands in a mirror (Maravita, Spence, Sergent, & Driver, 2002). Maravita et al (2002) investigated responses to vibrotactile stimulation of the hand during the presentation of congruent visual stimuli viewed directly or in a mirror: stimuli viewed in the mirror were presented near a reflection of the hands and stimuli viewed directly appeared in the absence of the hands at the same apparent distance from the participant. The actual hands were occluded during the task. They found that cross-modal interference was strongest when the visual distracter was presented near the reflection of the hands in the mirror, and this effect was not observed for the presentation of visual distracters located at an equivalent distance. Further experiments also failed to observe this effect in response to visual stimuli presented near a dummy hand or a hand belonging to somebody else and this finding suggests that the effect is specific to one's own limb. These studies indicate that the image of the hand is associated with personal space to the extent that the projection of the image into extrapersonal space will still result in personal space responses to the hand.

Comparable research exploring the projection of personal space to incorporate video images of the body has drawn similar conclusions. Iriki, Tanaka, Obayashi, and Iwamura (2001) found that the visual receptive field of bimodal cells in the intraparietal cortex of macaque monkeys will extend to incorporate the projected image of the monkey hand on the video screen. They argue that the video image is encoded as an extension to the representation of the body. Further research by Whiteley, Kennett, Taylor-Clarke, and Haggard (2004) has revealed that the bias towards the body observed by Hari and Jousmaki (1996) can be projected to include a bias for limbs presented on a video screen. These studies imply that the body schema can be projected to incorporate body images located beyond the realm of the physical body. These studies are highly relevant to the current thesis so they will be discussed in more detail in the following chapter.

Chapter 3

Flexibility of Bias towards Personal Space and Body Schema

Research outlined in Chapters 1 and 2 highlight the distinction between the body (personal space or body schema) and the world beyond the body (peripersonal and extrapersonal space), in addition to emphasising the flexible nature of this spatial coding. Of particular relevance to the experiments conducted in this thesis, Hari and Jousmaki (1996) found that motor activity is initiated more efficiently in response to stimuli located on the body, and Whiteley, Kennett, Taylor-Clarke, and Haggard (2004) revealed that this bias could be projected to incorporate video images of the body.

Hari and Jousmaki (1996) noted that participants in some of their previous research had reported feeling more 'comfortable' completing finger lift responses to stimuli located on the fingers. In response to this observation, they devised a method to explore responses to stimuli located on and off a responding limb. Eight participants (male/female ratio 4/4; mean age 30 years; right-handed; normal or corrected vision) were tested in this study. Participants were asked to position their index fingers either side of a central fixation point on a cardboard strip: their fingers were located in a central position (directly either side fixation), near lateral position (5cm from fixation on either side), or far lateral position (15cm from fixation on either side). Visual targets were presented directly to the left or right of fixation with random intervals of 2.5-3.5 seconds. The target would appear on the finger during the central position condition (target and fingers located directly either side of fixation). The target would appear off the finger during the near lateral and the far lateral conditions (target located directly either side of fixation and fingers located 5cm or 15cm from fixation). Participants were required to respond to each target by lifting the finger located in the same side of space as the target as quickly as possible and reaction times were recorded for each response. Hari and Jousmaki (1996) found that responses were significantly faster in the central condition (target located on the fingers). Subsequent control experiments investigated the potentially confounding effects of differences in hand separation and foveal proximity of the fingers. The first experiment presented targets on the fingers (central position) or 5cm above the fingers and found that responses were still faster for stimuli located on the fingers. This finding suggested that the bias for stimuli located on the fingers could not be due to differences in hand separation. The second experiment required participants to respond to auditory stimuli in the left or right ear and found that responses did not differ between the central and lateral positions. The third experiment required the participants to position their index fingers either 5cm or 10cm from fixation while the target appeared 10cm from fixation and found that responses were still faster for stimuli located on the fingers. These findings suggest that the bias for stimuli located on the fingers could not be due to the proximity of the fingers to fixation and foveal vision. Hari and Jousmaki (1996) concluded that these findings demonstrate one type of spatial stimulus-response compatibility. They proposed that stimuli located off the body required additional processing unnecessary for stimuli located on the responding body part. An alternative explanation for these findings is that there is an attention bias towards the body and, therefore, towards stimuli associated with the body.

Whiteley, Kennett, Taylor-Clarke, and Haggard (2004) replicated the study by Hari and Jousmaki (1997) in order to distinguish between these two potential explanations. Twelve participants were fitted with a pair of LEDs along the extended index finger of the left hand, and instructed to observe a screen displaying either the finger with LEDs or a finger-shaped block with LEDs. An upper or lower LED was illuminated and the participant responded to the target by executing a forced choice key press with the concealed right hand. This method controlled for potential spatial-attention and compatibility effects. They found significantly faster reaction times in response to a target located on the index finger of the participant relative to a target located on the neutral finger-shaped block. They attributed these results to an attention bias toward stimuli located on the body.

Further research by Whiteley, Spence, and Haggard (2007) has attempted to expand on the above study to investigate whether the observed effect is due to biological saliency, egocentric body representation, or a social/interpersonal body schema. They conducted three experiments adopting a similar design to the experiments completed by Whiteley et al (2004). Real-time video footage displayed two LED's attached to an actual finger or a finger-shaped block and participants were required to press one of two response keys with their non-stimulated hand to indicate the location of the lit LED. Participants in the first and second experiment were presented with video images of their own finger or the block. Participants in the first experiment were not exposed to any movement of the finger prior to the experimental trials whereas participants in the second experiment were exposed to passive movements of their finger or the block prior to the trials. It was proposed that this passive movement would encourage the participants to attribute the video image of their finger to themselves. The first experiment found no difference in responses to stimuli on the fingers or the block whereas the second experiment found that responses were faster for the stimuli located on the fingers relative to the block. This finding initially appears to conflict with the earlier research by Whiteley et al (2004) as they found evidence of preference for stimuli located on the fingers despite the absence of specific movement prior to the trials. However, it is noted by Whiteley et al (2007) that the participants in the original research were exposed to a familiarisation stage prior to the experimental trials during which the participants were likely to have attributed the filmed hands to themselves (participants in the first experiment described above did not experience any prior familiarisation with the video image hands). Participants in the third experiment were presented with video images of their own fingers, the fingers of the experimenter, or a finger-shaped block. Participants in this experiment were also exposed to passive movements of the fingers or block prior to the trials. This experiment again found that responses to the fingers were faster than responses to the block, although it did not reveal a significant difference between responses to the fingers of the participant and responses to the fingers of the experimenter (although descriptive analysis did reveal a smaller effect for the fingers of the experimenter). Whiteley et al (2007) concluded that the observed effect is not simply due to biological saliency, but rather it is a combination of an interpersonal body effect (action in any body) and an egocentric effect (action in ones own body).

The findings of Whiteley et al (2004) and Whiteley et al (2007) suggest that the bias towards stimuli located on the body can be projected beyond the physical body under certain circumstances (in this case, the bias is projected to incorporate a video image of the limbs). There is not, however, any research to date to suggest that this bias can include alternative representations of the body or external objects associated with the body. This chapter will explore the potential flexibility of spatial coding with regard to the bias towards the body observed by Hari and Jousmaki (1996).

Experiments 1 and 2 adapted the Hari and Jousmaki (1996) method to investigate this bias in a simulated environment. Virtual reality is an ideal medium for research in this area as it permits controlled presentation of stimuli in a rich and complex setting. Virtual representations can be conveniently manipulated to explore body space and schema as almost all aspects of the virtual image are under the control of the experimenter: visual appearance, spatial location, proprioceptive feedback, and participants' ability to control the virtual representation. Experiments 1 and 2 are essentially direct replications of the original Hari and Jousmaki (1996) study, adapted to determine whether a similar bias could be associated with the virtual hands.

Experiment 1: Spatial Coding of Virtual Limbs

Previous research (Hari and Jousmaki, 1996; Whiteley et al, 2004; Whiteley et al, 2007) has noted dissociation between responses to a target located on the body and responses to a target located off the body. Experiment 1 modified this design, replacing physical index fingers with virtual ones, in order to ascertain whether responses to a target located on the virtual hand would be faster than responses to a target located near the virtual hand.

Participants

Twenty-four participants (male/female ratio 6/18; aged between 18 and 25 years; right-handed; normal or corrected vision) were tested in this experiment. Each participant was tested alone and each experimental session lasted approximately one hour. Participants who were involved in the experiments reported in this thesis were selected via opportunity sampling methods from the population of undergraduate psychology students. All students received course and printer credits in return for their participation. Each participant received written and verbal instructions detailing the exact procedure of the experiment in accordance with ethical guidelines; although the hypothesis for this study was omitted in order to ensure that participants remained naïve. Informed consent was obtained prior to the initiation of the experiment and extensive debriefing was provided after the completion of the experiment. All of the experiments reported in this thesis were submitted and subsequently approved by the Ethics Committee of the University of Wales Bangor.

Method

Participants were tested in a simulated 3D environment generated via an Immersive Virtual Reality System by Sense8 WorldUp Release 5 under the guidance of a Polhemus 3Space Fastrak Motion Tracking System. The participant was seated before a table and fitted with an I-Visor Personal Display System over the head and an adjustable plastic finger strap around the middle of each extended index finger (see Figure 1 for photographs of the apparatus). The I-Visor Personal Display System had a screen refresh rate of 60hz. Lightweight 5DT sensors were fixed to the front of the headset and the top of each finger strap and the Fastrak Motion Tracking System monitored the position (X, Y and Z cartesian coordinates) and the orientation (azimuth, elevation and roll) of each sensor. The Fastrak System operated in real time with 4 ms latency and an update rate of 40hz. A transmitter acted as a reference frame for receiver measurements by emitting a magnetic field across a range of ten feet. Each sensor was detected in this magnetic field and a precise measurement of the position and orientation of the head and hands was calculated. This data was relayed to a Panrix Power PC in order to map a spatial correspondence between the physical movements of the participant and the visual presentation of the virtual world: movement of the head resulted in a concurrent variation of perspective and movement of the hands resulted in a concurrent movement of the virtual hands.

Figure 1

Virtual Reality Apparatus: I-visor personal display system with a lightweight 5DT sensor fixed to the front of the headset and adjustable plastic finger strap around the middle of each extended index finger with a 5DT sensor fixed to the top of each strap.

The virtual environment was presented to the participant through the visual display panel in the headset (see Figure 2 for screenshots of the display). The transmitter provided a reference point for all stimuli in the virtual world. The transmitter was measured at zero and all surrounding stimuli were measured in accordance with their distance from the transmitter. The transmitter was not illustrated in the virtual world. The virtual world appeared as a small room defined by three brick-effect walls. One virtual tabletop was presented in the centre of the virtual room: the tabletop was wood-effect and measured a perceived size of approximately 70cm in width and 110cm in length. Two square finger rests with a perceived size of 1.5cm x 1.5cm and one round fixation point with a perceived diameter of 1cm were located on the tabletop. The finger rests were displayed symmetrically 5cm lateral to the central fixation point: the lower finger rests were located 5cm below the level of fixation and the upper finger rests were located 5cm above the level of fixation. Two virtual hands were mapped to the physical hands of the participant: each virtual hand was fixed with the index fingers and thumbs extended and the middle, ring and little fingers pressed flat to the palms of the hands. The participant was instructed to activate the lower finger rests by placing the tips of the virtual index fingers on top of the finger rest squares. Each trial was initiated in response to the activation of the finger rests. One visual target materialised over an upper or lower finger rest to the left or right of fixation after the trial had been initiated. The target was a green sphere with a perceived diameter of approximately 1cm. The target appeared off the virtual finger when it was located over an upper finger rest and on the virtual finger when it was located over a lower finger rest. The participant was instructed to respond to the target as quickly as possible by lifting the same-sided index finger irrespective of whether the target had appeared over the upper or lower rest. The visual target disappeared after contact between the tip of a virtual index finger and a finger rest had been broken. Reaction times and number of errors were recorded to conclude the trial.

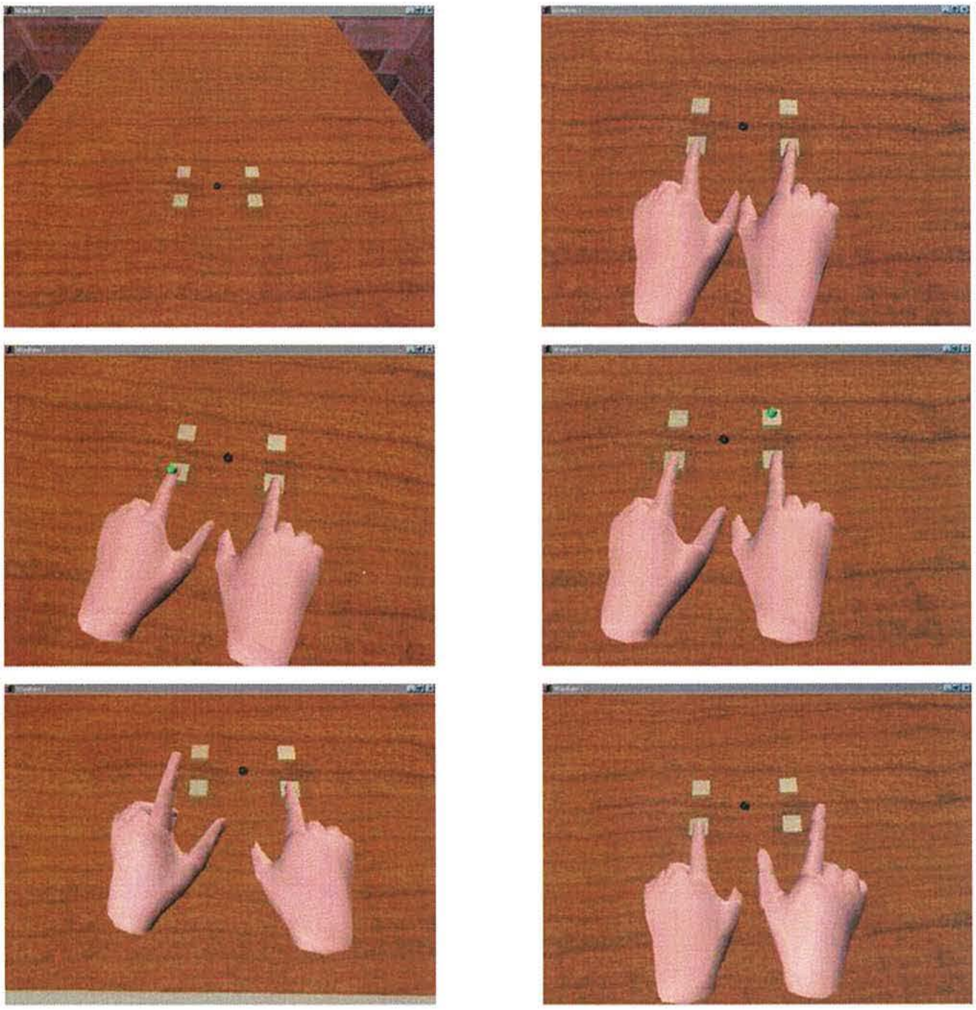

Figure 2

Screenshots of the Virtual Environment: Images by row from left to right illustrate the simulated environment, virtual limbs, target located on the virtual limb, target located off the virtual limb, response by the left limb, and response by the right limb.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 factorial design. The independent variables were the Target Side (Left or Right) and the Target Location (Lower Rests or Upper Rests). The dependent variable in this study was reaction time (measured in milliseconds as the time span between the appearance of the target and the break in contact between a virtual finger and a rest).

Results

RT (ms) data obtained in this experiment was subjected to descriptive (mean) and inferential (ANOVA) statistical analysis. Analysis excluded 8.15% of trials. Excluded data included errors consisting of responses by the incorrect hand and outliers. Outliers were expelled by repeatedly eliminating data with reaction times greater or less than three standard deviations from the calculated mean for each participant in each condition until all scores were located within three standard deviations. There was insufficient error data for meaningful analysis as accuracy measured 99%. Mean reaction time across all conditions for all participants measured 504ms.

Analysis investigated the factors Target Side and Target Location. Analysis indicated that responses to a target located on a virtual finger (lower rests) were faster than responses to a target located near a virtual finger (upper rests). There was a significant main effect of Target Location ($F(1,23) = 8.55$, $p = .008$): responses to a target located on the lower rests (M = 501ms) were significantly faster than responses to a target located on the upper rests (M = 507ms). Analysis also indicated a significant main effect of Target Side ($F(1,23) = 121.72$, $p = .001$): responses with the right hand (M = 480ms) were significantly faster than responses with the left hand (M = 528ms).

This experiment found that responses to a target located on a virtual limb are faster than responses to a target located near a virtual limb. This experiment did not, however, control for eye movements by ensuring that the participants maintained central fixation. Danckert and Goodale (2001) noted an advantage for processing information located in the lower visual field relative to the upper visual field, and they argued that this may indicate a functional bias for controlling movements. Although the findings of the current experiment have been interpreted in terms of preferential processing of stimuli located on the limb, these results could be explained equally well in terms of preferential processing of stimuli located in the lower visual field.

Experiment 2: Spatial Coding of Virtual Limbs
Baseline for Comparison with Subsequent Experiments

Experiment 2 modified the design of Experiment 1 to control for visual field effects. As in Experiment 1, this experiment aimed to determine whether responses to a target located on the virtual hand are faster than responses to a target located near the hand, while controlling for processing differences between upper and lower visual fields.

Participants

Twenty-four participants (male/female ratio 12/12; aged between 18 and 25 years; right-handed; normal or corrected vision) were tested in this experiment. All of the participants recruited for this experiment (and all subsequent experiments) had been screened to ensure that they had not taken part in any other experiments included in this thesis. This precaution was essential in order to be certain that the participants remained naïve about the true aim of the research and allow an appropriate comparison between different experiments.

Method

As in Experiment 1, participants were tested in a simulated 3D environment generated via an Immersive Virtual Reality System. The virtual world appeared as a small room defined by three walls around one large tabletop (see Figure 3 for screenshots of the virtual environment). Two square finger rests were displayed symmetrically at either side of a central fixation point on the tabletop: the inner finger rests were located 5cm lateral to fixation and the outer finger rests were located 10cm lateral to fixation. Two virtual hands were mapped to the physical hands of the participant: each virtual hand was fixed with the index fingers and thumbs extended and the middle, ring and little fingers pressed flat to the palms of the hands. The participant was instructed to activate either the inner or outer finger rests by placing the tips of the virtual index fingers on top of the finger rest squares. Each trial was initiated in response to the activation of the finger rests. One visual target materialized over an inner or outer finger rest to the left or right of fixation after the trial had been initiated. The target appeared off the virtual finger when the target was located over an inner finger rest and the fingers were located on the outer finger rests or when the target was located over an outer finger rest and the fingers were located on the inner finger rests. The target appeared on the virtual finger when the target and the fingers were located over the inner finger rests or when the target and the fingers were located over the outer finger rests. The participant was instructed to respond to the target as quickly as possible by lifting the same-sided index finger irrespective of whether the target had appeared over the inner or outer rest. The visual target disappeared after contact between the tip of a virtual index finger and a finger rest had been broken. Reaction times and number of errors were recorded to conclude the trial.

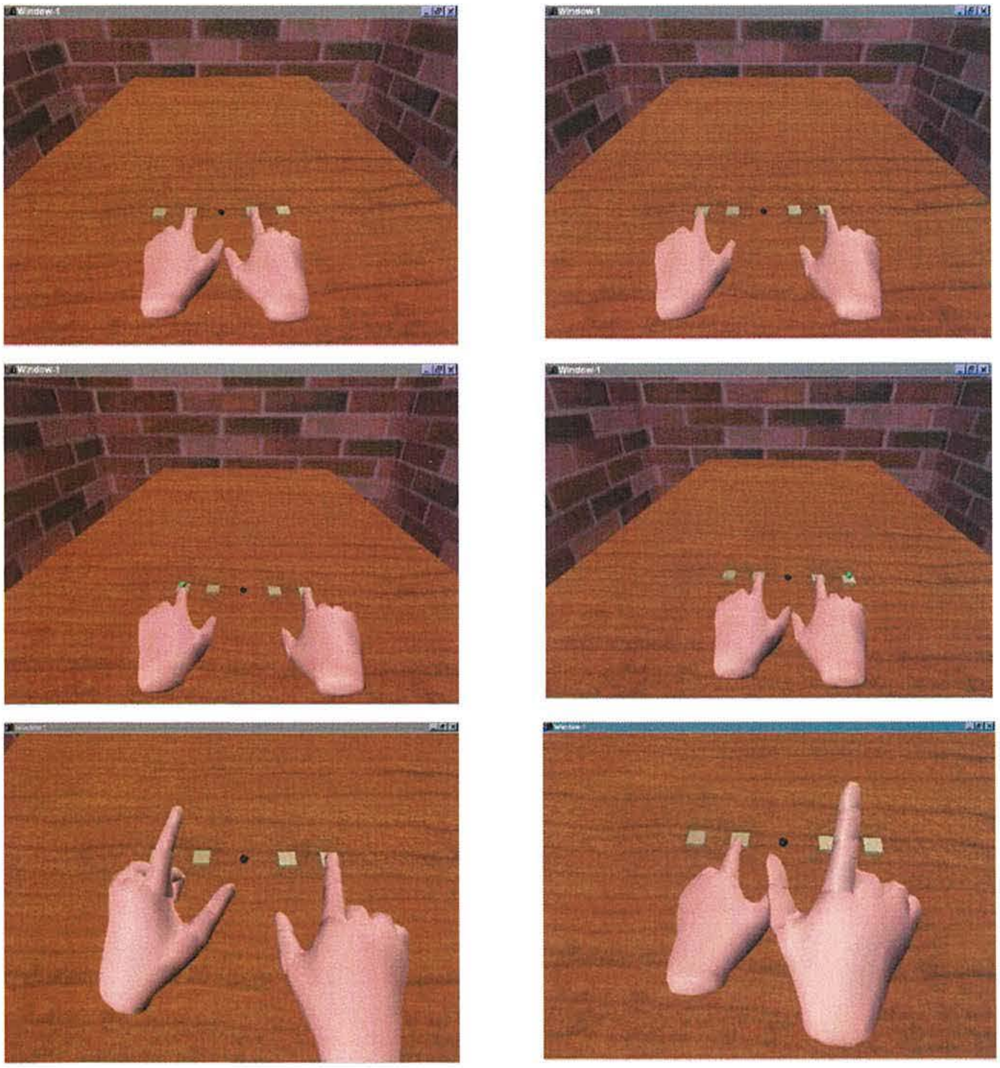

Figure 3

Screenshots of the Virtual Environment: Images by row from left to right illustrate the virtual limbs on inner rests, virtual limbs on outer rests, target located on the virtual limb, target located off the virtual limb, response by the left limb, and response by the right limb.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent variables in this study were the Target Side (Left or Right), Target Location (Inner Rests or Outer Rests), and Finger Location (Inner Rests or Outer Rests). Target Side and Target Location variables were presented randomly within each block while the Finger Location variable was presented according to the block of trials (fingers rested on the inner rests for Block A and outer rests for Block B - blocks were counterbalanced between participants). As in the previous experiment, the dependent variable in this study was reaction time (ms).

Results

RT (ms) data obtained in this experiment was subjected to descriptive (mean) and inferential (ANOVA) statistical analysis. Analysis excluded error data consisting of responses by the incorrect hand and data with reaction times greater or less than three standard deviations from the mean (9.06% of trials excluded). There was insufficient error data for meaningful analysis as accuracy measured 98%. Mean reaction time across all conditions for all participants measured 521ms. Please refer to Appendix 1 (Figure 33) for mean RT across all experiments.

The primary focus of this experiment was to determine any difference in response to targets located on versus off the virtual limb. This analysis was completed by collapsing the factors Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger (on finger consisted of responses to a target located on the same rest as the fingers whereas off finger consisted of responses to a target located on a different rest to the fingers). Analysis indicated that responses to a target located on a virtual finger were faster than responses to a target located near a virtual finger. There was a significant main effect of On/Off Finger ($F(1,23) = 10.60$, $p = .003$): responses to a target located on the finger (M = 514ms) were significantly faster than responses to a target located off the finger (M = 528ms).

Analysis also investigated the relationship between Target Location and Finger Location in order to further explore the on/off effect outlined above. As illustrated in Figure 4, analysis indicated a significant interaction between Target Location and

Finger Location (*F*(1,23) = 9.59, *p* = .005). Responses by a finger located on an inner rest were significantly faster when the target appeared over an inner rest (M = 494ms) as opposed to an outer rest (M = 513ms) (*t*(23) = -5.60, *p* = .001). Similarly, responses by a finger on an outer rest were faster when the target appeared over an outer rest (M = 536ms) as opposed to an inner rest (M = 545ms), although this difference did not reach significance (*t*(23) = 1.13, *p* = .270). This finding shows that the on/off effect is smaller when the fingers are located on the outer rests, although the overall interaction supports the on/off effect observed above.

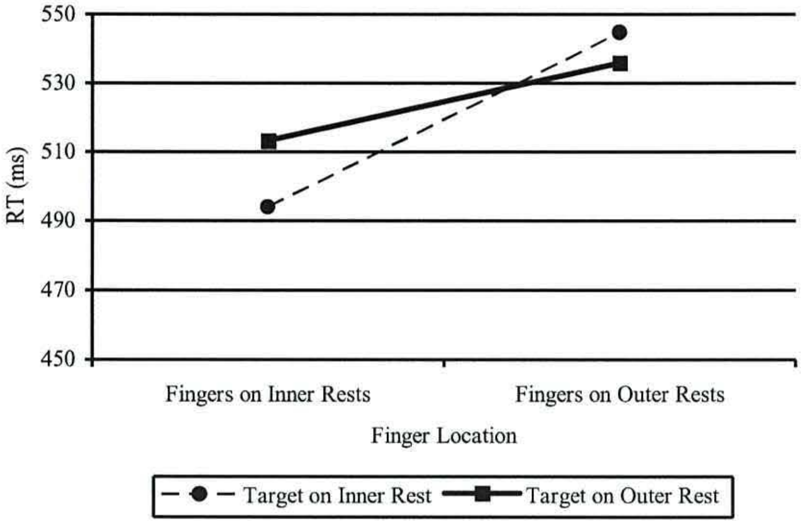

Figure 4

Mean RT (ms) as a function of Target Location and Finger Location in Experiment 2.

Additional analysis investigated the variables in order to identify any other main effects or interactions. The analysis revealed a significant main effect of Target Side (*F*(1,23) = 186.30, *p* = .001): responses with the right hand (M = 490ms) were significantly faster than responses with the left hand (M= 553ms). Analysis also revealed a significant main effect of Finger Location (*F*(1,23) = 11.35, *p* = .003): responses by fingers located on the inner rests (M = 504ms) were significantly faster than responses by fingers located on the outer rests (M = 540ms). These findings suggest that responses to a target are faster if the response is made by the right hand and the fingers are located closer to fixation. Analysis also indicated a significant interaction between Target Side and Target Location (*F*(1,23) = 4.85, *p* = 0.038) and a significant interaction between Target Side and Finger Location (*F*(1,23) = 5.06, *p* = .034). These findings indicate that responses on the right side were influenced more by the location of the target (right side responses were faster when the target was located on the inner rest), whereas responses on the left side were influenced more by the location of the responding fingers (left side responses were faster when the fingers were located on the inner rest). Please refer to Appendix 4 (Table 2) for all of the main effects and interactions, and Appendices 5 and 6 (Table 3 and Table 4) for the means and standard errors in each condition.

This experiment found that responses to a target located on a virtual limb were faster than responses to a target located near a virtual limb. These results replicate those of Experiment 1 demonstrating that the space on the virtual limb is represented differently from the space near the virtual limb. This finding suggests that there are features specific to the virtual limbs which encourage preferential processing of this spatial region.

Conclusion

The research reviewed in the previous chapter highlighted the flexibility of spatial coding and body representation. Evidence suggests that objects located near the body can be recoded as though they are located some distance from the body and, conversely, objects located far from the body can be recoded as though they are located near the body. Similarly, evidence suggests that the body schema is a malleable entity capable of projecting beyond the physical body (Holmes, Calvert, & Spence, 2004). Experiments described in this chapter aimed to further investigate the flexibility of space and schema by exploring the bias towards the body observed by Hari and Jousmaki (1996) and these studies revealed a similar bias towards virtual limbs in a simulated environment. Hari and Jousmaki (1996) found that responses to stimuli located on the limb were approximately 20-40 milliseconds faster than responses to stimuli located near the limb. Experiments 1 and 2 found that responses to stimuli located on the virtual limb were respectively 6 and 14 milliseconds faster than responses to stimuli located near the virtual limb. This reduced difference in reaction times relative to the study conducted by Hari and Jousmaki (1996) can be explained in terms of the distinction between the real and virtual limbs: it may be the case that the preference for stimuli associated with the virtual limbs is less distinct than the preference for stimuli associated with real limbs. However, despite this difference in the size of the observed effect, it is important to note that both the previous study and the current research revealed a similar pattern of results indicating an advantage for stimuli located on the real and virtual body.

The results of these experiments may be taken as tentative evidence for the flexibility of the body schema. Hari and Jousmaki (1996) found that responses to objects located on the body are faster than responses to objects located near the body. It could be suggested that responses are biased towards stimuli associated with the body schema and located within the realm of personal space. The experiments described in this chapter found that responses to targets located on the virtual hands are also faster than responses to targets located near the virtual hands. This similarity between responses to the physical hands and responses to the virtual hands could suggest that the virtual limb is processed in a similar way to the physical limb. It may, therefore, be argued that the virtual limb has been incorporated into the body schema; although possibly to a lesser extent than the real limbs (as indicated by the reduced effect noted in the current experiments relative to the Hari and Jousmaki study) since the virtual limbs are a relatively new addition to the body schema whereas the real limbs have existed as part of the schema since birth. In these experiments, the physical hand and the virtual hand occupied the same spatial location so it would be inaccurate to suggest that personal space had been projected, although experiments in subsequent chapters will displace the virtual hand so any bias identified in these studies may demonstrate a projection of personal space to incorporate the hands. In this context, 'incorporation' is operationally defined as the projection of personal space to space outside the physical body or the alteration of the body schema to include objects outside the physical body.

It would appear that the bias observed in Experiments 1 and 2 is specific to the virtual limbs since the results indicate an advantage for stimuli located on the finger relative to the finger rest. It would, therefore, seem likely that there is a set of features to direct this bias toward the virtual limbs. The experiments in the subsequent chapters will explore these potentially critical features by adapting the method established in Experiment 2 to investigate changes in visual appearance, spatial overlap, controllability, and tactile feedback. Results from Experiment 2 will serve as a baseline and each of these subsequent studies will be compared with this experiment in order to determine the effect of these feature changes on the advantage for targets located on the hand.

Chapter 4

Role of Visual Appearance and Spatial Location in the bias towards the Virtual Limbs

Experiments completed in the previous chapter revealed that responses to a target located on a virtual limb are faster than responses to a target located near the virtual limb. These findings are taken as tentative evidence for the incorporation of the virtual limb into the body schema. Research investigating the flexibility of personal space and the malleability of the body schema in relation to objects beyond the body has explored the role of visual appearance and spatial location (see below for review of research).

Research investigating the rubber hand illusion has attempted to identify those features necessary for the individual to experience false sensation from the artificial limb. There is evidence to suggest that this illusion may be dependent on the similarity in physical appearance and orientation between the real hand and rubber hand. Tsakiris and Haggard (2005) found that the rubber hand illusion was significantly impaired in experiments adopting neutral objects, incongruent rubber hand identity, and incongruent rubber hand posture. Research also failed to observe cross-modal interference by distracters located near a rubber hand spatially misaligned with the physical hand (Pavani, Spence, & Driver, 2000; Austen, Soto-Faraco, Enns, & Kingstone, 2004) and evidence from patient studies revealed that misaligned rubber hands positioned in an incompatible or implausible posture did not elicit cross-modal visuo-tactile extinction (Farne, Pavani, Meneghello, & Ladavas, 2000). Further research did not observe primate neural activity in response to the sight of an unrealistic or misaligned fake arm located above a hidden real arm, although activity was observed in response to the sight of a real arm and a realistic fake arm (Graziano, Cooke, & Taylor, 2000). This research suggests that the visual appearance and spatial orientation of the rubber hand is crucial for the production of this illusion. It may, therefore, be argued that an object visually distinct from a real limb and/or spatial incongruent with a real limb will not be accepted as part of the body. Contrary evidence, however, has been presented to suggest that it is possible to elicit a rubber hand type illusion with an object not resembling an actual body part. Ramachandran, Hirstein, and Rogers-Ramachandran (1998) and Armel and Ramachandran (2003) reported a rubber hand type illusion in response to synchronous stroking of a hidden real hand and a table.

Research into the effects of tool use would also appear to support the theory that an external object not resembling an actual body part can be incorporated into the body schema or result in a projection of personal space. Iriki, Tanaka, and Iwamura (1996) noted that bimodal neurons responsible for coding the hand schema could be modified by the use of a hand held rake to the extent that the neurons would begin to fire in response to stimuli located close to the tool. They concluded that the rake had been incorporated into the hand schema and personal space had been extended along the length of the tool. As noted in Chapter 2, these conclusions have been criticised by Holmes and Spence (2004) and further research in the field of tool use has suggested that the use of tools does not lead to an 'extension' of peripersonal space, but rather a 'projection' of peripersonal space (Holmes, Calvert, & Spence, 2004). It is clear that the objects utilised in these tool studies (such as rakes and sticks) do not bare any resemblance to actual body parts, yet these experiments still observe neurological and behavioural responses to suggest that these objects are linked to the physical body (Berti & Frassinetti, 2000; Farne & Ladavas, 2000; Iriki, Tanaka, & Iwamura, 1996; Maravita, Spence, Kennett, & Driver, 2002). These findings would imply that an object dissimilar from the body, yet under the control of the individual, can be incorporated into the body schema.

Research exploring projected images of the limbs (video images, shadows, etc) has highlighted the flexibility of the body schema and personal space with regards to the spatial location of the projected image. Experiments investigating responses to video images of limbs have found a projection of the visual receptive field of bimodal cells to include the video image in macaque monkeys (Iriki, Tanaka, Obayashi, & Iwamura, 2001) and a behavioural bias towards stimuli located on the video image in humans (Whiteley, Kennett, Taylor-Clarke, & Haggard, 2004). These studies imply that the body schema can be projected to incorporate images spatially displaced from the body. Further evidence from Pavani and Castiello (2003) revealed that personal space could be projected along the length of a body shadow. This study could be taken as evidence to suggest that the body schema had projected to incorporate a shadow stretching some distance away from the body. However, it should also be noted that this incorporation of the hand shadow was found to be subject to the visual appearance of the shadow: dressing the physical hand in a misshapen glove in order to distort the hand shadow eliminated the effect observed in this study.

Hari and Jousmaki (1996) found that motor activity is initiated more efficiently in response to stimuli located on the responding limb and experiments in the previous chapter replicated this study using virtual limbs to reveal that motor activity is also initiated more efficiently in response to stimuli located on a virtual limb. It was noted in the conclusion of Chapter 3 that the observed bias appears to be specific to the virtual limbs since an advantage was recorded for stimuli located on the limbs as opposed to the table or rests. There is some evidence from past research to suggest that the visual appearance and spatial location of the virtual limbs may influence this advantage for targets located on the virtual hand. It is worth noting, however, that there are already minor discrepancies between the visual appearance and spatial location of the virtual limbs and the physical limbs (for instance, the virtual limbs are approximately 10% smaller than the physical limbs in order to make allowances for the small screen size in the headset) and these inconsistencies did not appear to affect the bias towards the virtual hands in the previous two experiments.

Experiments 3 – 6 further examined the roles of visual appearance and spatial location of the virtual objects in the response preference for stimuli located on the virtual limbs: Experiment 3 presented the virtual limbs as mirror images of hands; Experiment 4 presented the virtual limbs as feet; Experiment 5 presented the virtual limbs as cones; and Experiment 6 presented the virtual limbs some distance in front of the real limbs.

Experiment 3: Virtual Limbs as Mirror Hands

Experiment 3 investigates the visual appearance of the virtual limb by substituting realistic virtual hands for virtual hands located at an impossible angle (akin to a mirror image of hands). Experiment 2 suggested that stimuli associated with the virtual hands will receive preferential processing. This experiment explored the importance of visual appearance by replicating the method of Experiment 2, but changing the appearance of the virtual limbs by reversing their orientation. Misalignment of rubber hands has been previously shown to disrupt the rubber hand illusion (Tsakiris & Haggard, 2005) so this experiment was conducted to determine whether misalignment of the virtual hands would disrupt the bias for stimuli located on the hand.

Participants

Twenty-four participants (male/female ratio 9/15; aged between 18 and 45 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

As in Experiments 1 and 2, participants were tested in a simulated 3D environment generated via an Immersive Virtual Reality System by Sense8 WorldUp Release 5 under the guidance of a Polhemus 3Space Fastrak Motion Tracking System. This experiment also adopted the same stimuli and design as Experiment 2 with one crucial difference in the appearance of the virtual hands. In Experiment 3, virtual hands were presented as a mirror image of the physical hands (the physical index fingers pointed away from the body whereas the virtual index fingers pointed towards the body - the tips of the physical index fingers and the virtual index fingers occupied the same spatial location) and participants were instructed to respond to the virtual target located on or near the tip of the virtual index finger by lifting the same-sided virtual hand (see Figure 5 for screenshots of the virtual environment). Participants were encouraged to interpret the visual stimuli as though they were watching the movement in a mirror.

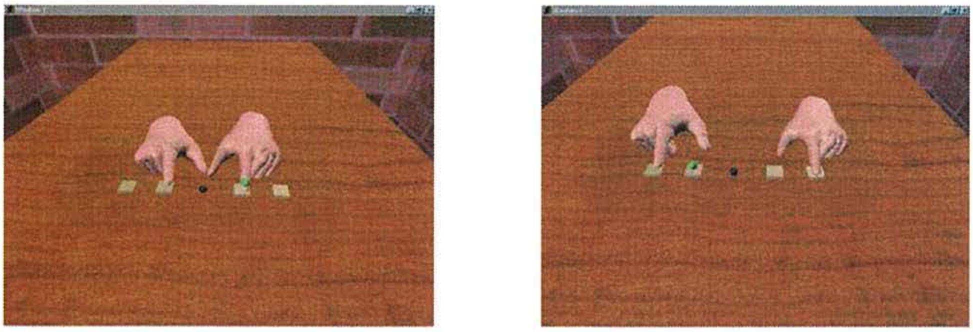

Figure 5

Screenshots of the Virtual Environment: Images from left to right illustrate the target located on the virtual limb and the target located off the virtual limb.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent variables in this study were the Target Side (Left or Right with respect to the participant – similar to a mirror), Target Location (Inner Rests or Outer Rests), and Finger Location (Inner Rests or Outer Rests). Target Side and Target Location variables were presented randomly within each block while the Finger Location variable was presented according to the block of trials (fingers rested on the inner rests for Block A and outer rests for Block B - blocks were counterbalanced between participants). The dependent variable in this study was reaction time (measured in milliseconds as the time span between the appearance of the target and the break in contact between a virtual finger and a finger rest).

Results

The data were analysed as in Experiment 2. There was insufficient error data for meaningful analysis as accuracy measured at 99%. Analysis of reaction time data excluded 8.81% of trials. Mean reaction time across all conditions for all participants measured at 618ms. Please refer to Appendix 1 (Figure 33) for mean RT across all experiments.

The primary aim of this experiment was to determine any difference in response to targets located on versus off the virtual limb and compare this difference to the findings of Experiment 2. This analysis was completed by collapsing the independent variables Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger. Analysis indicated that responses to a target located on a virtual finger were faster than responses to a target located near a virtual finger. There was a significant main effect of On/Off Finger ($F(1,23) = 4.59$, $p = .043$): responses to a target located on the finger (M = 613ms) were significantly faster than responses to a target located off the finger (M = 623ms).

Between-experiment analysis compared these findings to the results of Experiment 2 in order to determine whether the change in visual appearance reduced the advantage for targets located on the virtual limb. Analysis did not reveal a significant interaction ($F\ (1,46) = 0.36$, $p = .55$) between Target Location and Experiment suggesting that there is no difference between the effect observed in Experiment 2 and the effect observed in Experiment 3. Power analysis, however, revealed that the level of power could have been too low to detect a true difference (power = .09). It is possible that an alternative result would have been obtained if more participants had been tested. It can, therefore, be concluded that Experiments 2 and 3 each obtained a significant on/off effect, although the exact nature of this effect may have been different across the two experiments. Between-experiment analysis also found significant main effects of Target Location ($F(1,46) = 14.24$, $p = .001$) and Experiment ($F(1,46) = 41.84$, $p = .001$). RT in Experiment 2 (M = 521ms) was significantly faster than in Experiment 3 (M = 618ms). It is worth noting, however, that accuracy in Experiment 3 (99%) was marginally higher than Experiment 2 (98%) suggesting a possible speed/accuracy tradeoff. Indeed, several participants commented on the unusual orientation of the hands in Experiment 3 so it is likely that they moved more slowly in order to ensure an accurate response.

Analysis also investigated the relationship between Target Location and Finger Location in order to further explore the on/off effect outlined above. Analysis revealed a significant interaction between Target Location and Finger Location ($F(1,23) = 5.06$, $p = .034$). As illustrated in Figure 6, this interaction shows that responses by the fingers on the inner rest were fastest when the targets were on the inner rests and responses by the fingers on the outer rests were fastest when the targets were on the outer rests. Responses by a finger on an outer rest were significantly faster when the target appeared over an outer rest (M = 605ms) as opposed to an inner rest (M = 618ms) ($t(23) = 3.70$, $p = .001$). Responses by a finger on an inner rest were faster when the target appeared over an inner rest (M = 620ms) as opposed to an outer rest (M = 627ms), although this difference was not significant (*t*(23) = -1.02, *p* = .319). It is interesting to note that the results of the paired samples t-test in this experiment differ from the previous experiment: Experiment 2 found a significant effect for fingers located on the inner rests, whereas Experiment 3 found a significant effect for fingers. It is, however, important to acknowledge that descriptive analysis revealed that the trend in the data was the same for fingers located on the inner and outer rests in both experiments: responses were faster if the fingers and the targets occupied the same rest.

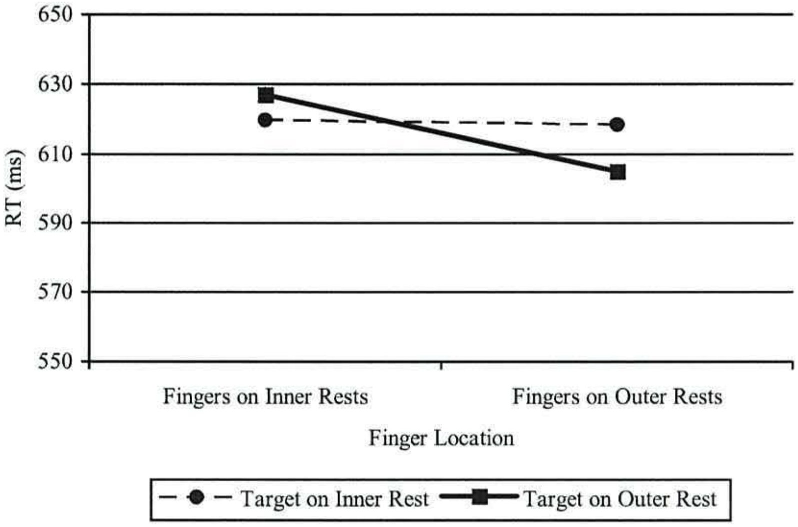

Figure 6
Mean RT (ms) as a function of Target Location and Finger Location in Experiment 3.

Further analysis investigated the factors Target Side, Target Location, and Finger Location in order to identify any other noteworthy main effects or interactions. Analysis found a significant three-way interaction between Target Side, Target Location, and Finger Location (*F*(1,23) = 9.11, *p* = .006). The fastest response was recorded on the right side of fixation when the fingers and the target were located on the outer rests whereas the slowest response was recorded on the left side of fixation when the fingers were located on the inner rests and the targets were located on an outer rest.

In conclusion, this experiment found that responses to a target located on a virtual limb were faster than responses to a target located near a virtual limb. These results indicate that stimuli located on a virtual hand positioned at an impossible angle will receive preferential processing. This finding suggests that the spatial orientation of the virtual object is not a critical feature for responses to be biased towards the object.

Experiment 4: Virtual Limbs as Feet

Experiment 4 investigates the visual appearance of the virtual limb by substituting virtual hands for virtual feet. The study described above suggests that stimuli located on virtual hands will receive preferential processing, irrespective of the spatial orientation of the hands. This experiment explored the importance of visual appearance by replicating the method of Experiment 2, but changing the appearance of the virtual limbs by having them appear as an alternative body part. This experiment was conducted to determine whether the appearance of the virtual limbs as feet would disrupt the bias for stimuli located on the limbs.

Participants

Twenty-four naïve participants (male/female ratio 6/18; aged between 18 and 25 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 4 adopted the same design, utilized the same apparatus, and used similar stimuli to Experiment 2. The crucial difference in the stimuli employed in this experiment was the appearance of the virtual hands. In Experiment 4, virtual limbs were presented as feet and participants were instructed to respond to the virtual target by lifting the same-sided virtual foot (see Figure 7 for screenshots of the virtual environment).

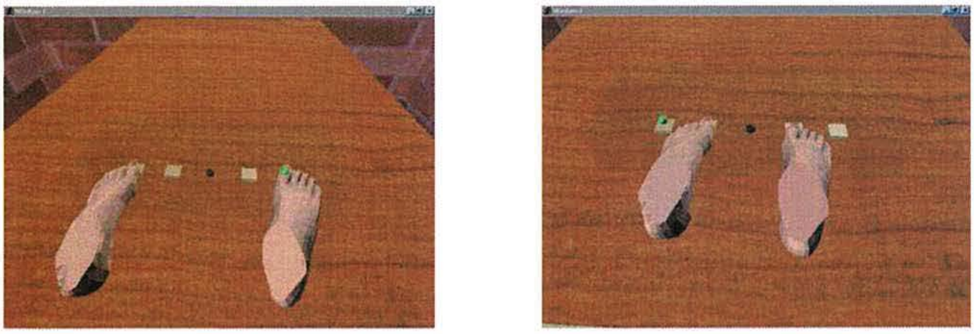

Figure 7

Screenshots of the Virtual Environment: Images from left to right illustrate the target located on the virtual foot and the target located off the virtual foot

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent and dependent variables in this study were the same as Experiment 2.

Results

The data were analysed as in Experiment 2. There was insufficient error data for meaningful analysis as accuracy measured at 99% Analysis of RT data excluded 9.03% of trials. Mean RT measured at 602ms. Please refer to Appendix 1 (Figure 33) for mean RT across all experiments.

This experiment aimed to investigate differences in responses to targets located on versus off the virtual limb. This analysis was completed by examining the independent variables Target Location and Feet Location in terms of whether the target was located on or near the virtual toe. Analysis indicated a significant main effect of On/Off Toe ($F(1,23) = 6.87$, $p = .015$): responses to a target located on the toe (M = 596ms) were significantly faster than responses to a target located off the toe (M = 607ms).

Between-experiment analyses compared these findings to the results of Experiment 2 in order to determine whether the change in visual appearance reduced the advantage for targets located on the limb. Analyses did not reveal a significant interaction ($F(1,46) = 0.17$, $p = .682$) and these findings suggest that the visual appearance of the virtual limbs did not affect the observed bias. Power analysis, however, revealed that the level of power could have been too low to detect a true difference (power = .07). As in Experiment 3, analysis revealed that Experiments 2 and 4 each obtained a significant on/off effect, although the exact nature of this effect may have been different across the experiments. Between-experiment analysis also found a significant main effect of Target Location (*F*(1,46) = 17.24, *p* = .001) and Experiment (*F*(1,46) = 22.1, *p* = .001). RT in Experiment 2 (M = 521ms) was significantly faster than in Experiment 4 (M = 602ms). As noted in the previous experiment, this result may have been due to a speed/accuracy tradeoff as accuracy was again found to be greater in Experiment 4 (99%) than in Experiment 2 (98%).

Analysis also investigated the relationship between Target Location and Feet Location in order to further explore the on/off effect outlined above. As in the previous experiment, analysis revealed a significant interaction between Target Location and Feet Location (*F*(1,23) = 6.57, *p* = .017). In this experiment, however, although responses by a toe on an outer rest were considerably faster when the target appeared over an outer rest (M = 594ms) as opposed to an inner rest (M = 630ms), responses by a toe on an inner rest were faster when the target appeared over an outer rest (M = 585ms) as opposed to an inner rest (M = 598ms). This interaction is illustrated in Figure 8. This finding was unusual as the on/off effect was not observed for feet located on the inner rests. It is important to acknowledge, however, that the overall pattern of results still lends support to the suggestion that responses are slightly more biased towards stimuli located on the virtual feet.

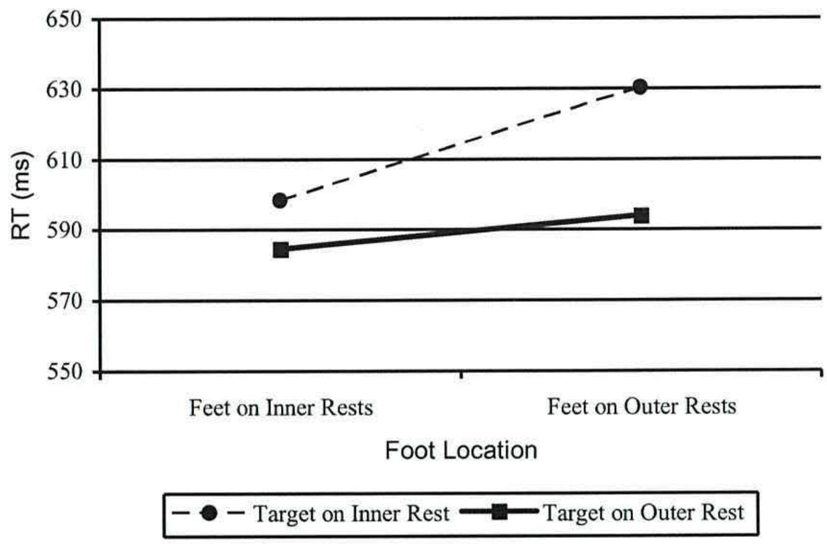

Figure 8

Mean RT (ms) as a function of Target Location and Feet Location in Experiment 4

Further analysis of Experiment 4 investigated the factors Target Side, Target Location, and Feet Location in order to identify any other noteworthy main effects or interactions. Analysis found a significant main effect of Target Side (*F*(1,23) = 25.31, *p* = .001): responses on the right side (M = 582ms) were significantly faster than responses on the left side (M = 62ms); and a significant main effect of Target Location (*F*(1,23) = 34.79, *p* = .001): responses to a target located on an outer rest (M = 589ms) were significantly faster than responses to a target located on an inner rest (M = 614ms). These findings suggest that responses to a target are faster if the response is made by the right hand and the target is located further from fixation. Please refer to Appendix 4 (Table 2) for all of the main effects and Appendices 5 and 6 (Table 3 and Table 4) for the means and standard error in each condition.

In summary, this experiment found that responses to a target located on a virtual foot were faster than responses to a target located near a virtual foot. These results indicate that the previously observed preferential processing is not limited to virtual representations of the hands. This finding further supports the suggestion that visual appearance is not a critical feature for responses to be biased towards a virtual object.

Experiment 5: Virtual Limbs as Cones

Experiment 5 further investigates the visual appearance of the virtual limb by substituting virtual hands for virtual cones. The two experiments described previously suggest that stimuli associated with virtual objects appearing as a body part will receive preferential processing. This experiment explored the importance of visual appearance by replicating the method of Experiment 2, but changing the appearance of the virtual limbs by having them appear as a non-body part. Synchronous stroking of a neutral object, as opposed to a realistic rubber hand, has failed to elicit the rubber hand illusion (Tsakiris & Haggard, 2005) so this experiment aimed to determine whether a neutral object (such as a cone) could elicit the on/off effect.

Participants

Twenty-four naïve participants (male/female ratio 10/14; aged between 18 and 45 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 5 adopted the same design, utilized the same apparatus, and employed similar stimuli to Experiment 2. The crucial difference in this experiment was again the appearance of the virtual hands. In Experiment 5, virtual limbs were presented as white cones and participants were instructed to respond to the virtual target by lifting the same-sided virtual cone (see Figure 9 for screenshots of the virtual environment).

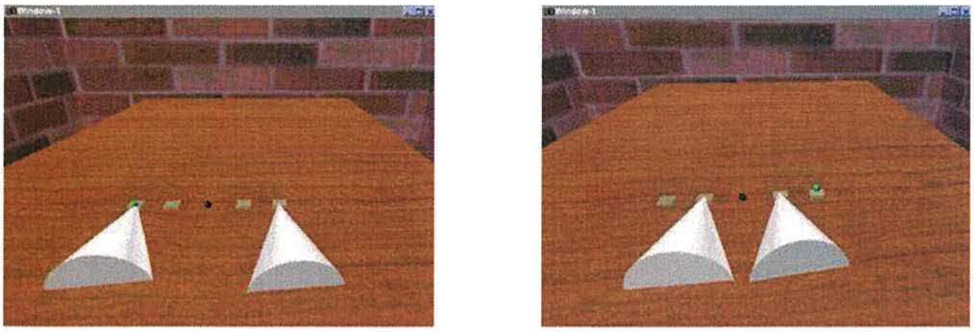

Figure 9

Screenshots of the Virtual Environment: Images from left to right illustrate the target located on the virtual cone and the target located off the virtual cone.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent and dependent variables in this study were the same as Experiment 2.

Results

The data were analysed as in Experiment 2. There was insufficient error data for meaningful analysis as accuracy measured at 98% Analysis of RT data excluded 8.79% of trials. Mean RT measured at 596ms.

As in previous experiments, this study aimed to determine any difference in response to targets located on versus off the virtual limb by examining the independent variables Target Location and Cone Location in terms of whether the target was located on the virtual cone or near the virtual cone. Analysis indicated a significant main effect of On/Off Cone ($F(1,23) = 6.17$, $p = .021$): responses to a target located on the cone (M = 592ms) were significantly faster than responses to a target located off the cone (M = 600ms).

Between-experiment analyses compared these findings to the results of Experiment 2 in order to determine whether the change in visual appearance reduced the advantage for targets located on the object. Analyses did not reveal a significant interaction ($F(1,46) = 1.39$, $p = 0.244$) indicating that the visual appearance of the virtual limbs did not affect the observed bias. Unfortunately, power analysis revealed that the level of power could have been too low to detect a true difference (power = .21), although this comparison was found to be more powerful than the between-experiment analysis reported in the previous two experiments. However, it is still possible that an alternative result could have been obtained if more participants had been tested thus it must be concluded that, although Experiments 2 and 5 each obtained a significant on/off effect, the exact nature of this effect may have differed across the two experiments. Between-experiment analysis also found a significant main effect of Target Location ($F(1,46) = 16.61$, $p = .001$) and Experiment ($F(1,46) = 11.57$, $p = .001$). In contrast to the previous two experiments, RT in Experiment 5 (M = 596ms) was significantly slower than in Experiment 2 (M = 521ms).

Analysis also investigated the relationship between Target Location and Cone Location in order to further explore the on/off effect outlined above. As suggested by the observed on/off effect, analysis revealed a significant interaction between Target Location and Cone Location ($F(1,23) = 6.05$, $p = .022$) . This interaction is illustrated in Figure 10. Responses by a cone on an inner rest were faster when the target appeared over an inner rest (M = 582ms) as opposed to an outer rest (M = 595ms), although this difference was not found to be significant ($t(23) = 1.51$, $p = .146$). Similarly, responses by a cone on an outer rest were faster when the target appeared over an outer rest (M = 604ms) as opposed to an inner rest (M = 608ms), although this difference was again not found to be significant ($t(23) = .46$, $p = .650$). It is, however, important to acknowledge that descriptive analysis revealed that the trend in the data was for faster responses if the fingers and the targets occupied the same rest and, although the paired samples t-test did not reveal any significant differences, the overall interaction was found to be significant.

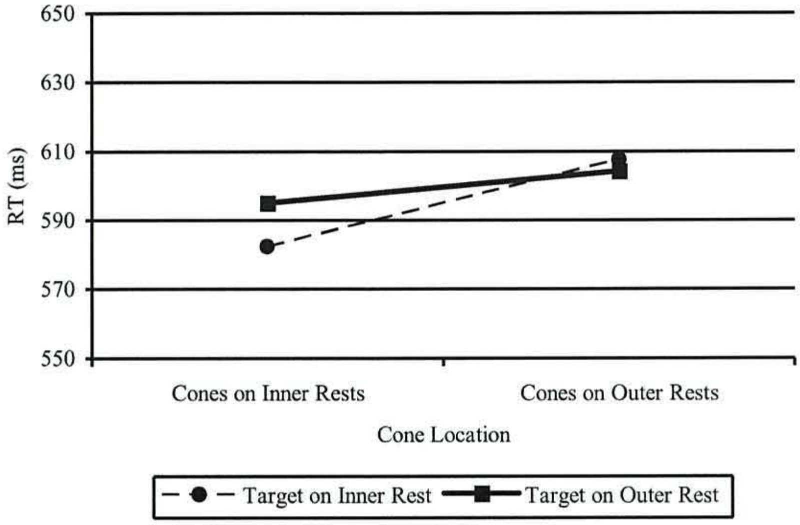

Figure 10
Mean RT (ms) as a function of Target Location and Cone Location in Experiment 5.

Further analysis of Experiment 5 investigated the factors Target Side, Target Location, and Cone Location to reveal a significant main effect of Target Side (*F*(1,23) = 46.65, *p* = .001): responses on the right side (M = 569ms) were significantly faster than responses on the left side (M = 626ms). Analysis also found a significant interaction between Target Side and Target Location (*F*(1,23) = 4.43, *p* = .046): responses by the left cone were faster when the target appeared over the outer rest (M = 624ms) as opposed to the inner rest (M = 628ms), whereas responses by the right cone were faster when the target appeared over the inner rest (M = 562ms) as opposed to the outer rest (M = 576ms).

To conclude, this experiment found that responses to a target located on a virtual cone were faster than responses to a target located near a virtual cone. These results indicate that stimuli located on a virtual object of any visual appearance will receive preferential processing. This finding offers additional support to the suggestion that visual appearance is not a critical feature for responses to be biased towards a virtual limb.

Experiment 6: Spatially Displaced Virtual Limbs

Experiment 6 investigates the spatial location of the virtual limb by substituting virtual hands spatially congruent with the real hands for virtual hands spatially displaced from the real hands. All of the experiments described previously suggest that stimuli located on virtual objects occupying the same spatial location as the real hands will receive preferential processing. On the basis of these findings it could be argued that the bias is for the region of space occupied by the real hands as this spatial region coincides with the space occupied by the virtual hands in all of the previous studies. Furthermore, in terms of the concept of personal space, these experiments did not require the participant to alter their spatial coding since the virtual limb appeared in the same spatial location as the physical body. It could not, therefore, be concluded in the previous studies that the participant had projected personal space to incorporate the virtual limb. Experiment 6, however, explored the importance of spatial location by replicating the method of Experiment 2, but displacing the virtual limbs by 50cm so that targets located both on and off the virtual hands were situated off the real hands. This experiment was able to investigate whether an on/off effect could be evoked in response to virtual limbs located in extrapersonal space, thus an observed effect in this study could indicate that personal space had been projected into extrapersonal space to incorporate the virtual limbs.

Participants

Twenty-four participants (male/female ratio 16/8; aged between 18 and 45 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 6 adopted the same design, utilized the same apparatus, and used similar stimuli to Experiment 2. The crucial difference in this experiment was the spatial location of the virtual hands. In Experiment 6, virtual limbs were presented 50cm in front of the physical limbs and participants were instructed to respond to the virtual target by lifting the same-sided virtual hand (see Figure 11 for screenshots of the virtual environment).

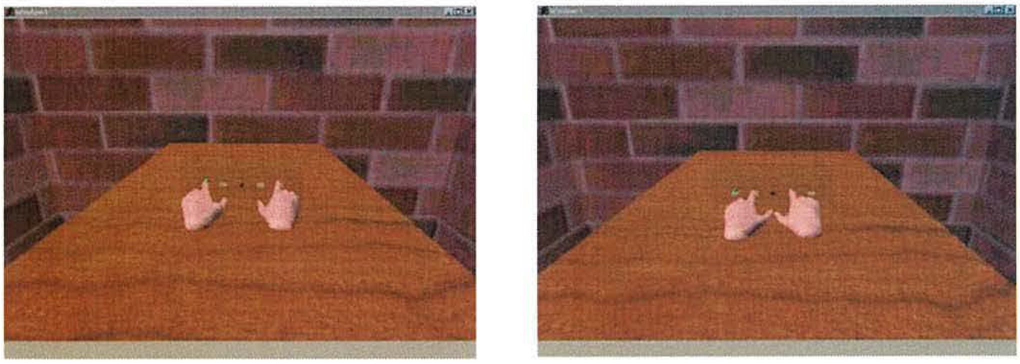

Figure 11

Screenshots of the Virtual Environment: Images from left to right illustrate the target located on the virtual limb and the target located off the virtual limb.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent and dependent variables in this study were again the same as Experiment 2.

Results

The data were analysed as in Experiment 2. There was insufficient error data for meaningful analysis as accuracy measured at 98% Analysis of RT data excluded 11.99% of trials. Mean RT measured at 732ms.

As in previous experiments, analysis aimed to determine any difference in response to targets located on versus off the virtual limb by examining the independent variables Target Location and Finger Location. Analysis revealed a significant main effect of On/Off Finger ($F(1,23) = 9.06$, $p = .006$): responses to a target located on the finger (M = 709ms) were significantly faster than responses to a target located off the finger (M = 754ms).

Between-experiment analyses compared these findings to the results of Experiment 2 in order to determine whether the change in spatial location influenced the advantage for targets located on the virtual limb. Analyses did not reveal a significant interaction (F (1,46) = 3.97, p = .05), although the level of probability was close to significant and further analysis found that the level of power could have been too low to detect a true difference (power = .5). It could, therefore, be suggested that the change in spatial location may have influenced the advantage for targets located on the hands to some extent. However, the observed effect was actually greater in Experiment 6 in comparison to Experiment 2 and this suggests that the change in spatial location enhanced, rather than reduced, the advantage for targets located on the virtual hands. Between-experiment analysis also found a significant main effect of Target Location (*F*(1,46) = 14.38, *p* = .001) and Experiment (*F*(1,46) = 34.22, *p* = .001). RT in Experiment 2 (M = 521ms) was significantly faster than in Experiment 6 (M = 732ms). This was not the result of a speed/accuracy tradeoff since accuracy was the same in Experiment 6 (M = 98%) and Experiment 2 (M = 98%). It is possible that participants simply found it more difficult to identify and respond to the distant target in this experiment (Downing & Pinker, 1985, found that target detections was slower for targets located in far space), although it is interesting to note that the overall increased reaction coincided with an increase in the bias towards stimuli located on the virtual limbs.

Analysis also investigated the relationship between Target Location and Finger Location in order to further explore the on/off effect. As expected, analysis indicated a significant interaction between Target Location and Finger Location (*F*(1,23) = 8.73, *p* = .007). This interaction is illustrated in Figure 12. Responses by a finger on an inner rest were significantly faster when the target appeared over an inner rest (M = 682ms) as opposed to an outer rest (M = 737ms) (t(23) = -5.95, p = .001). Similarly, responses by a finger on an outer rest were faster when the target appeared over an outer rest (M = 737ms) as opposed to an inner rest (M = 768ms), although this difference was not found to be significant (t(23) = 1.27, p = .217). It is interesting to note that the results of the paired samples t-tests in this experiment are similar to the findings of Experiment 2: both experiments found that responses by fingers located on the inner rests were significantly faster if the target occupied the same rest. It is, however, important to acknowledge that descriptive analysis revealed that the trend in the data was the same for fingers located on both the inner and outer rests, and the overall significant interaction supported the hypothesis that the responses are faster if the fingers and the targets occupy the same rest.

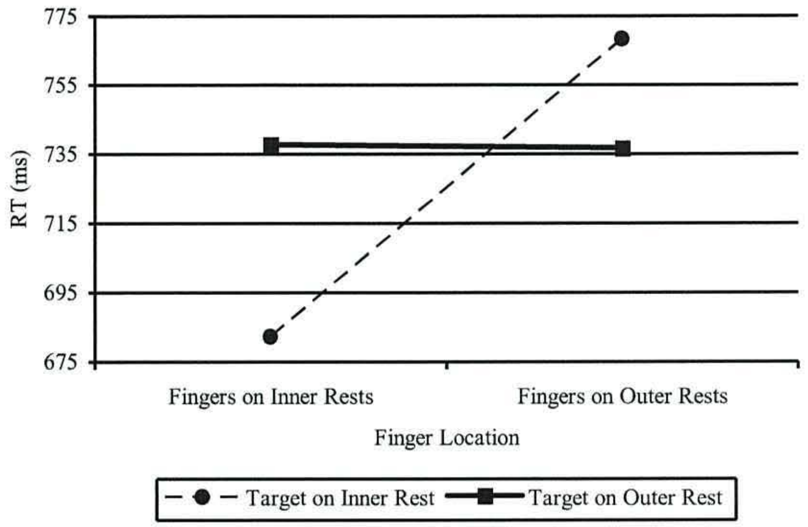

Figure 12
Mean RT (ms) as a function of Target Location and Finger Location in Experiment 6.

Further analysis investigated the factors Target Side, Target Location, and Finger Location to reveal a significant main effect of Target Side (*F*(1,23) = 8.26, *p* = .009): responses on the right side (M = 703ms) were significantly faster than responses on the left side (M = 759ms). This result supports the findings of the previous experiments by revealing that responses to the target are faster on the right side of space.

These results indicate that stimuli associated with virtual hands located some distance from the body also receive preferential processing. This finding suggests that spatial overlap between the physical hands and the virtual hands is not a necessary feature for responses to be biased towards the virtual limbs. This finding is particularly interesting since this experiment dissociates between the real hand and the virtual hand. Experiments described previously presented the virtual limb in the same location as the real hand thus they could not distinguish between responses to targets located on and off the real limb and responses to targets located on and off the virtual limb. In terms of the concept of personal space, these experiments did not require the participant to alter their spatial coding since the virtual limb appeared in the same location as the physical body. The current experiment, however, was able to focus specifically on the ability to project personal space. Targets in this experiment were located on or near a displaced virtual hand so they were never located on the real hand. The findings of this experiment indicate that the observed bias is specific to the targets situated on the virtual limb, rather than associated with targets situated in the same location as the real hand, thus it can be concluded that the participants were able to alter their coding of personal space to incorporate the virtual limbs located in extrapersonal space.

Conclusion

Experiments completed in the previous chapter found that responses to a target located on a virtual hand are faster than responses to a target located near the virtual hand. It was noted in the conclusion of this chapter that the observed bias is specific to the virtual limbs as opposed to other virtual objects present in the simulation and there must, therefore, be a specific set of features to direct this bias toward the virtual limbs. Experiments described in this chapter investigated the roles of visual appearance and spatial location of the virtual limbs as mediating factors in this effect. All of these experiments found a significant bias for stimuli located on the virtual limbs, as opposed to near the virtual limbs. The findings of these experiments suggest that there will be enhanced processing for stimuli associated with the virtual limbs, irrespective of the visual appearance, spatial orientation, and spatial location of the virtual limb.

Comparisons between the four experiments described in this chapter and the second experiment described in the previous chapter revealed that the on/off effects recorded in Experiments 3, 4, 5, and 6 were not significantly different from the effect observed Experiment 2. There were, however, some potential problems with this analysis as the levels of power for each comparison were found to be too low to accept that the analysis was capable of revealing a true difference. This finding suggests that there may have been some differences in the nature of the on/off effect observed across the different experiments, and this difference is particularly notable in Experiment 6 as the on/off effect was considerably greater in this study than in Experiment 2. Despite these potential problems in the comparisons, it is important to acknowledge that all of the experiments still demonstrated a significant on/off effect.

Comparative analysis also revealed a significant difference in mean reaction times: Experiments 3, 4, 5, and 6 were each found to record slower reaction times than Experiment 2. This finding may have been the result of a speed-accuracy trade-off in Experiments 3 and 4 since reduced RT corresponded with enhanced accuracy. It is interesting to note, however, that these increased reaction times did not appear to influence any of the observed on/off effects, except in the case of Experiment 6 when it actually coincided with an enhanced bias towards stimuli located on the virtual limb.

Additional analysis revealed a consistent bias for responses to targets located on the right side of fixation (indicated in Experiments 4, 5, and 6). Other findings were observed during analysis, although exploration of the results did not indicate any other findings consistent across numerous experiments or relevant to the main hypothesis of the study. Please refer to Appendix 3 (Table 1) for comparison of the on/off effect between experiments and Appendix 4 (Table 2) for comparison of all other observed effects.

The findings of the current experiments are consistent with the results of the research into tool use. Experimental evidence presented in this chapter reveals that the participant will demonstrate a bias for targets located on the virtual limb, irrespective of the visual appearance of the limb. Evidence from the research exploring the projection of the body schema and personal space to incorporate tools also suggests that visual appearance is irrelevant, while the active use of the tool to complete a particular task is crucial (Berti & Frassinetti, 2000; Farne & Ladavas, 2000; Iriki, Tanaka, & Iwamura, 1996; Maravita, Spence, Kennett, & Driver, 2002).

The findings of the current experiments are also consistent with the results of some of the research exploring the rubber hand illusion. Armel and Ramachandran (2003) found that a rubber hand type illusion could be evoked in response to synchronous stroking of a real hand and a table, thus suggesting that the visual appearance of the object is not crucial for the evocation of the illusion. Similarly, Austen, Soto-Faraco, Enns, and Kingstone (2004) suggest that there may be some flexibility in the visual appearance of a rubber hand. They explored the congruency effect noted in response to tactile targets located on the real finger or thumb during concurrent presentation of visual targets located on the finger or thumb of a fake hand. They found that the visual appearance of the rubber hand was flexible to the extent that the congruency effect remained despite the fact that there were striking visual differences between the real hand and the fake hand (in particular, the fake hand was made of a pink rubber glove and the congruency effect was not enhanced by placing a similar pink glove on the real hand). Furthermore, the congruency effect remained even when the fake hand was hidden from view. These findings suggest that the visual appearance of the object is not essential for the object to be incorporated into the body schema.

However, despite the supporting research noted above, the findings of the current experiments are in conflict with much of the research exploring the rubber hand illusion. Most of the rubber hand research suggests that the visual appearance of the rubber limb is crucial in order for the individual to experience illusory sensation from the fake hand (Farne, Pavani, Meneghello, & Ladavas, 2000; Graziano, Cooke, & Taylor, 2000; Pavani, Spence, & Driver, 2000; Tsakiris & Haggard, 2005). In particular, this research reveals that the rubber hand illusion is dependent on a postural congruency between the rubber hands and the real hands. Indeed, Austen, Soto-Faraco, Enns, and Kingstone (2004) revealed that, even though the rubber hand effect could be evoked in response to a hidden rubber hand, the observation of a posturally incongruent rubber hand was sufficient to disrupt the illusion. This observation is particularly inconsistent with the results of Experiment 3 as this study found an on/off effect in response to virtual limbs presented at an impossible angle.

It is proposed that, while the tool use and rubber hand research does offer evidence for the flexibility of the body schema and personal space, research in these areas are actually investigating different, though inevitably connected, underlying processes. Tool based research usually investigates control over an external object (commonly associated with a sense of agency) as the participant is required to actively manipulate the tool to complete a task. In contrast, early rubber hand research often investigated the receipt of sensory feedback from an external object (commonly associated with a sense of ownership) as the participant was required to observe the rubber hand being touched whilst feeling their real hand being touched. The virtual hand experiments discussed in this chapter required the participants to use the virtual limbs as tools to complete the task of responding to the target. It is, therefore, likely that the underlying mechanisms investigated in these studies are more akin to the tool research than the early rubber hand research. This proposition is supported in recent rubber hand research exploring the effects of active movement. Azanon and Soto-Faraco (2007) found that the rubber hand illusion could be evoked in response to a fake hand located in a posturally incongruent position to the real hand provided that the movement of the fake hand was linked to personal motor activity in the real hand. This finding suggests that the visual orientation of the rubber hand is less important if the individual is able to exercise some degree of control over the limb (as is the case in the tool research). These possibilities are explored in more detail during the subsequent experiments: Chapter 5 focuses on the role of control in the bias towards targets located on the virtual limbs and Chapter 6 focuses on the role of visuo-tactile sensation in the bias towards targets located on the virtual limbs.

Chapter 5

Role of Control in the bias towards the Virtual Limbs

Research presented in Chapter 1 suggests that body representation forms the fundamental basis for the psychological concept of the self. Body representation is presented as a complex schema designed to provide the individual with an integrated understanding of their own body based on visual, proprioceptive, and sensory information. Two factors associated with the creation of this comprehensive body schema relate to control over the body (often associated with a sense of agency) and sensory feedback from the body (often associated with a sense of ownership).

Agency has been defined as an awareness of your control over an action performed by your own body whereas ownership is defined as an awareness of an action performed by your own body (Gallagher, 2003). Agency is driven by efferent signals as it involves centrally generated actions whereas ownership is driven by afferent signal as it involves multisensory experiences (Tsakiris & Haggard, 2005). Crudely phrased, the difference between a sense of agency and a sense of ownership may be analogous to the difference between the feeling that 'I am moving my arm' and the feeling that 'my arm is moving'. There are, however, some theoretical issues to consider in the use of the terms 'agency' and 'ownership'. Research has adopted the term agency to refer to the feeling of control over an object and it is often assumed that this feeling of control will inevitably result from the experience of having control over an object. Similarly, research assumes that sensory feedback from the limb will inevitably lead to a feeling of ownership over the limb. It may seem natural to presume that the objective activity (such as controlling a limb) is automatically linked to the subjective experience (such as feeling control over a limb), but this assumption is inappropriate without valid empirical evidence. Indeed, it may be possible for an individual to control an object without experiencing a sense of agency and it may be possible for an individual to receive tactile feedback from a limb without experiencing a sense of ownership. In order to avoid delving into a potentially subjective discussion of the 'feeling' or 'sense' of agency, this chapter will focus on the issue of control as an objective event (either the participant does or does not have control over an object) rather than referring to the invocation of a feeling or sense of agency.

Research investigating space and schema has suggested that control over the body is essential for the creation of the body schema and the boundaries of personal space. Tsakiris, Prabhu, and Haggard (2006) adapted the method used in the rubber hand studies for application with projected images of a physical hand. They asked participants to move their own index finger (efferent information), experience their index finger being moved by the experimenter (afferent information), or experience tactile stimulation of their index finger. Participants were presented with synchronous or asynchronous projections of the hand. Rubber hand illusions were found to be greater in synchronous trials for all conditions, with the effect spreading across the whole hand, rather than remaining restricted to the index finger, for the active movement condition. Further research by Tsakiris, Haggard, Franck, Mainy, and Sirigu (2005) adopted a similar method to investigate self-recognition. Participants were asked to move their own index finger (efferent information) or experience their index finger being moved by the experimenter (afferent information) while watching a projection of their own hand or the hand of the experimenter. Tsakiris et al (2005) found that participants correctly identified their own hand more frequently when they had obtained efferent information and concluded that control over the body is crucial for a unified representation of the body.

Research investigating the flexibility of space and schema has suggested that an external object can be incorporated into the body schema and that personal space can be projected to incorporate an external object provided that the individual has exercised some element of control over the object. Studies exploring the use of tools have suggested that both space and schema can be manipulated to incorporate a tool following the experience of control over the tool (Berti & Frassinetti, 2000; Farne & Ladavas, 2000; Iriki, Tanaka, & Iwamura, 1996; Maravita, Spence, Kennett, & Driver, 2002). This tool research is similar to the experiments considered in the previous two chapters in that both types of study involve the participant exercising control over an object in order to complete a task (Experiments 1 to 6 required the participants to control the virtual limbs in order to lift them in response to a target).

All research investigating flexibility of personal space and the body schema should consider the role of control and it is particularly crucial that studies investigating the potential of tools (virtual or physical) discuss their findings with regards to the issue of control. Experiments described in the previous two chapters concluded that there will be enhanced processing for stimuli associated with the virtual limbs, irrespective of the visual appearance, spatial orientation, and spatial location of the limb. All of these experiments allowed the participant to consistently and predictably control the virtual limbs to complete the task. This chapter will discuss whether this control is responsible for the preference for stimuli associated with the virtual limbs or, more specifically, whether this preference will remain in the absence of control. Experiments 7 – 12 will examine the role of control in the response preference for stimuli located on the virtual limbs: Experiment 7 investigates the absence of control by making the virtual hands immobile; Experiment 8 investigates the importance of predictability of control by making the movement of the virtual hands unpredictable; Experiments 9 and 10 investigate the flexibility of control by placing each virtual hand under the control of the opposite physical hand; Experiment 11 investigates the importance of the controlling limb by placing the virtual limbs under the control of the feet; and Experiment 12 investigates the potential for 'second-hand' control by placing virtual objects under the control of a physical tool wielded by the participant.

Experiment 7: Immobile Virtual Limbs

Experiment 7 investigates the absence of control by making the virtual hands immobile. The results from the previous experiments suggest a "permissive" approach to the bias towards targets located on the virtual limbs: neither the appearance nor apparent location of the virtual limb seems to affect the on/off effect. This experiment explored the importance of control over the virtual limbs by replicating the method of Experiment 2, but removing the element of control by making the virtual hands immobile. In this way, Experiment 7 and 2 are perceptually identical in terms of the appearance of the target on and off the virtual hand; but in the current experiment, participants have no control or possibility for moving the virtual hand.

Participants

Twenty-four participants (male/female ratio 9/15; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 7 adopted the same design, utilized the same apparatus, and used the same stimuli as Experiment 2. The crucial difference in this experiment was the controllability of the virtual hands. In Experiment 7, virtual hands remained immobile so that the participant could not exercise any kind of control over the limbs (see Figure 13 for screenshots of the virtual environment).

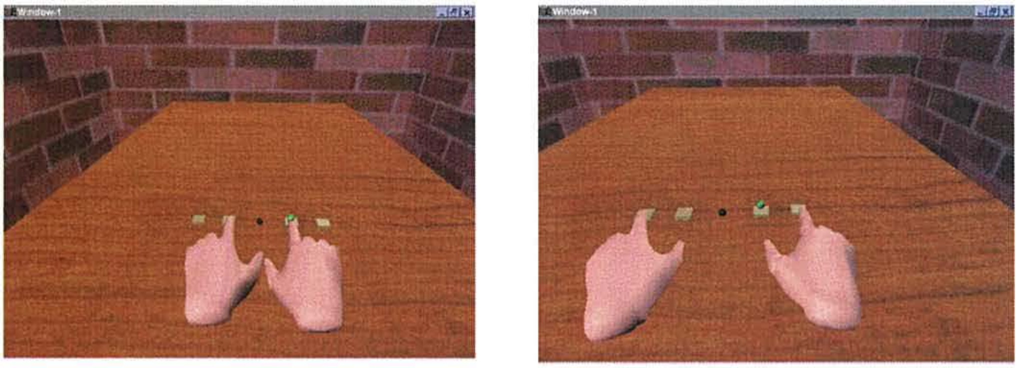

Figure 13
Screenshots of the Virtual Environment: Images from left to right illustrate the target located on the virtual limb and the target located off the virtual limb.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent and dependent variables in this study were again the same as Experiment 2.

Results

The data were analysed as in Experiment 2. There was insufficient error data for meaningful analysis as accuracy measured at 98% Analysis of RT data excluded 8.72% of trials. Mean RT measured at 530ms. Please refer to Appendix 1 (Figure 33) for mean RT across all experiments.

As in previous experiments, analysis aimed to determine any differences in response to targets located on versus off the virtual limb by examining the independent variables Target Location and Finger Location. Analysis did not find a significant main effect of On/Off Finger (*F*(1,23) = 0.1, *p* = .761): responses to a target located on the finger (M = 530ms) were the same as responses to a target located off the finger (M = 530ms).

Between-experiment analyses compared these findings to the results of Experiment 2 in order to confirm whether the change in controllability reduced the advantage for targets located on the virtual limbs. Analyses explored the factors Experiment (Experiment 2 and Experiment 7) and On/Off Effect to reveal a significant interaction (F (1,46) = 9.14, p = .004) indicating that there was a significant difference between the effect observed in Experiment 2 and the absence of effect observed in Experiment 7. Analysis also found a significant main effect of Target Location (F(1,46) = 7.48, p = .009). Analysis did not reveal a main effect of Experiment and this finding shows that there is no significant difference between the mean reaction times in Experiment 2 (M = 521ms) and Experiment 7 (M = 530ms). These experiments are visually identical during the presentation of the target and the only difference occurs when the participant responds to the target by lifting their hand. Since the virtual hand is immobile in Experiment 7, this design is conceptually identical to the off finger condition of Experiment 2. In Experiment 2, the target can appear on the virtual hand or on the table (off the virtual hand). In Experiment 7, the target can again appear on or off the virtual hand, but there is nothing to distinguish the virtual hand from the table in either condition because the hand remains immobile throughout. In short, both on and off finger conditions in Experiment 7 and the off finger condition in Experiment 2 all involve a target presented on an uncontrollable object (either hand or table). It is interesting to note, therefore, that the mean reaction times are similar for the off and on hand conditions in Experiment 7 (off hand M = 530ms; on hand M = 530ms) and the off hand condition in Experiment 2 (M = 528ms). The crucial difference between these two experiments lies in the on hand condition of Experiment 2 when the reaction times are considerably faster (M = 514ms), hence the significant interaction noted above. This finding suggests that the differences in reaction times observed in all of the previous experiments are indeed due to the fact that the participant can exercise control over the virtual limb.

Analysis also investigated the relationship between Target Location and Finger Location. As predicted by the absence of a significant on/off effect, analysis did not reveal a significant interaction between Target Location and Finger Location (F(1,23)

= .05, *p* = .823). The relationship between Target Location and Finger Location is illustrated in Figure 14.

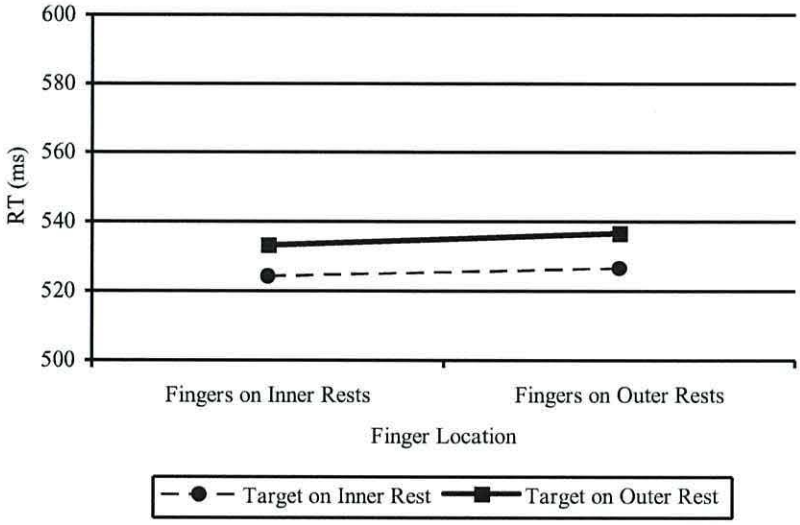

Figure 14
Mean RT (ms) as a function of Target Location and Finger Location in Experiment 7.

Further analysis of Experiment 7 investigated the factors Target Side, Target Location, and Finger Location in order to identify any additional noteworthy main effects or interactions. Analysis revealed a significant main effect of Target Side (*F*(1,23) = 85.99, *p* = .001): responses on the right side (M = 508ms) were significantly faster than responses on the left side (M = 553ms); and Target Location (*F*(1,23) = 17.24, *p* = .000): responses to targets located on the inner rests (M = 525ms) were significantly faster than responses to targets located on the outer rests (M = 535ms). These findings suggest that responses to a target are faster if the response is made by the right hand and the target is located on the inner rest. Analysis of these results also indicated a significant three-way interaction between Target Side, Target Location, and Finger Location (*F*(1,23) = 13.09, *p* = .001): the fastest responses were recorded on the right side when the fingers and the target were located on the inner rests whereas the slowest responses were recorded on the left side when the fingers and the target were located on the outer rests. Please refer to Appendix 4 (Table 2) for all of the main effects and interactions, and Appendices 5 and 6 (Table 3 and Table 4) for the means and standard errors in each condition.

This experiment found that responses to a target located on an immobile virtual limb were not faster than responses to a target located near an immobile virtual limb, and this finding was found to be significantly different to the bias for targets located on the controllable virtual limb observed in Experiment 2. These results reduce the possibility of a perceptual account to explain the bias for stimuli located on the virtual limbs since both Experiments 2 and 7 were perceptually identical during the presentation of the target. Instead, these findings suggest that it may be necessary for the virtual hand to be under the control of the participant in order for responses to be biased towards the limb. These findings could, however, also be attributed to the perceptual differences between the two experiments during the response to the target. It is possible that the effect observed in Experiment 2 indicates a bias towards moving (or potentially moving) objects, rather than objects under the control of the participant.

Experiment 8: Unpredictable Control Virtual Limbs

In Experiments 1 through 6, movements of the real hand produced predictable movements of the virtual hand and all of these investigations found a bias toward stimuli located on the hand. In Experiment 7, movements of the real hand did not result in any movement of the virtual hand and this study found that a bias did not exist toward an immobile hand. This result could, however, be explained by a perceptual account (bias towards potentially moving objects) or a control account (bias towards controllable objects). Experiment 8 investigated these two potential explanations by making the movement of the virtual hands unpredictable. In this experiment, constant control was replaced by unpredictable control: virtual hands would unpredictably either move according to the real hands, or remain immobile. This experiment would ensure that the participant was presented with potentially moving limbs, yet not grant absolute control over the limbs during the response.

Participants

Twenty-four participants (male/female ratio 13/11; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 8 adopted the same design, utilized the same apparatus, and used the same stimuli as Experiment 2. The crucial difference in this experiment was the predictability of the control over the virtual hands. In Experiment 8, virtual hands were randomly either mapped to the hands of the participant (50% of trials) or remained immobile on the table surface (50% of trials).

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 x 2 factorial design. The independent variables in this study were the Target Side (Left or Right), Target Location (Inner Rests or Outer Rests), Finger Location (Inner Rests or Outer Rests), and Control (Virtual Hands Controlled or Immobile). Target Side, Target Location, and Control variables were presented randomly within each block while the Finger Location variable was presented according to the block of trials (fingers rested on the inner rests for Block A and outer rests for Block B - blocks were counterbalanced between participants).

Results

The data were analysed as in Experiment 2 with the additional factor of Control. There was insufficient error data for meaningful analysis as accuracy measured at 98% Analysis of RT data excluded 10.43% of trials. Mean RT measured at 755ms.

As in previous studies, this experiment aimed to determine any differences in response to targets located on versus off the virtual limb. This analysis was completed by examining the independent variables Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger. Analysis indicated that there was no significant main effect of On/Off Finger ($F(1,23) = 2.88$, $p = .103$): indeed, responses to a target located on the finger (M = 553ms) were, if anything, slower than responses to a target located off the finger (M = 546ms).

Between-experiment analyses compared these findings to the results of Experiment 2 to reveal a significant interaction between Experiment 8 and Experiment 2 ($F\ (1,46) =$

12.83, *p* = .001). As in the previous experiment (Experiment 7 – immobile virtual hands), this finding shows that unpredictable control over the virtual limbs reduced the advantage for targets located on the object. This result reduces the possibility of a perceptual explanation for the effect observed in Experiment 1. This experiment was visually identical to Experiment 2 during the controlling limb trials and the sole difference between the two experiments was that the participant could not reliably predict the movement of the virtual limb. Predictable control is essential in order for one to perceive an object as a tool to complete a task rather than an incidental feature of the environment. This experiment prevented the participant from exercising this degree of control over the virtual hands thus the participant did not exhibit a bias towards stimuli located on the limbs.

In order to explore the influence of control on the bias towards targets located on the virtual hands, it was necessary to compare responses in the trial following a controllable trial or an immobile trial (excluding the first trial of each block). Control could not be analysed directly by comparing responses in controllable trials with responses in immobile trials because the participant was not aware that they had control over the virtual limb until they had moved the limb in reaction to the target. Analysis investigated the factors On/Off Finger and Control During Previous Trial to reveal no significant main effects or interactions. Responses to a target located on a virtual finger and responses to a target located near a virtual finger were found to be equally similar in those trails following controllable trials (On M = 555; Off M = 546ms) and those trials following immobile trials (On M = 550ms; Off M =546ms) (*F*(21,23) = .42, *p* = .523).

Additional analysis investigated the factors Target Side, Target Location, Finger Location, and Control to reveal a significant main effect of Target Side (*F*(1,23) = 5.93, *p* = .023): responses on the right side (M = 539) were significantly faster than responses on the left side (M = 560); and Target Location (*F*(1,23) = 15.62, *p* = .001): responses to a target located on an inner rest (M = 539) were significantly faster than responses to a target located on an outer rest (M = 559). These findings suggest that responses to a target are faster if the response is made by the right hand and the target is located on the inner rest.

This experiment found that overall responses to a target located on an unpredictable virtual limb were slower than responses to a target located near an unpredictable virtual limb. Furthermore, this experiment revealed that there was no difference in the responses to targets located on and off the virtual limbs following control trials or immobile trials. These results indicate that stimuli associated with an unpredictable virtual limb do not receive preferential processing and this suggests that it is necessary for the virtual limb to be under the constant and reliable control of the participant in order for responses to be biased towards the limb. This finding suggests that the on/off effect is not the result of a bias towards potentially moving objects since the effect was not observed in this experiment when the participant was presented with randomly moving virtual limbs. Instead, these findings suggest that the on/off effect is dependent on the participant exercising predictable control over the virtual limbs or, at the very least, experiencing reliable movement of the limbs in accordance with their own actions.

Experiment 9: Crossed Control Virtual Limbs Virtual Response

Experiment 9 investigated the flexibility of control by placing each virtual hand under the control of the opposite physical hand. Participants in this experiment were instructed to respond with the same-sided virtual limb (this response required the participant to move the opposite physical limb). In Experiments 1 through 6, virtual limbs were controlled by the ipsilateral hand. This experiment explored whether other forms of control would result in the on/off effect, such as control of the limbs by the contralateral hand. In short, can the mapping between movements of the controlling (physical) limb and the virtual limb be specified in a flexible manner? Experiment 9, therefore, aimed to replicate Experiment 2 replacing virtual hands under the control of the same-sided physical hands (spatially compatible control) with virtual hands under the control of the opposite physical hands (spatially incompatible control).

Participants

Twenty-four participants (male/female ratio 8/16; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 9 adopted the same design, utilized the same apparatus, and used the same stimuli as Experiment 2. The crucial difference in this experiment was the spatial compatibility of the control over the virtual hands. In Experiment 9, virtual hands were mapped to the physical hands of the participant with each of the virtual hands under the control of the opposite physical hand – movement of the right physical hand resulted in an equivalent movement of the left virtual hand and movement of the left physical hand resulted in an equivalent movement of the right virtual hand. In this experiment, the participant was instructed to respond to the target as quickly as possible by lifting the same-sided virtual index finger (this action was completed by lifting the opposite-sided physical finger).

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent and dependent variables in this study were the same as those employed in Experiment 2.

Results

The data were analysed as in Experiment 2. Analysis of RT data excluded 9.76% of trials. Mean accuracy measured at 90%. Responses in this study were considerably less accurate when compared with the previous experiments. This finding is possibly a result of the contralateral control exercised over the virtual hands since the natural bias is likely to be to respond with the ipsilateral hand. Evidence for this natural persuasion can be observed in the Simon Effect (Simon & Small, 1969). Mean RT measured at 647ms.

Analysis of this experiment examined the independent variables Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger. In this case, unlike in the previous two experiments, analysis did reveal a significant main effect of On/Off Finger ($F(1,23) = 5.04$, $p = .035$): responses to a target located on the finger (M = 635ms) were significantly faster than responses to a target located off the finger (M = 659ms). It was appropriate to explore the possibility of a speed-accuracy trade-off in this experiment since accuracy was considerably different to the previous studies. Analysis did not, however, indicate any trade between speed and accuracy: performance was both faster and more accurate in the On condition (RT M = 635ms; Accuracy M = 91%) than in the Off condition (RT M = 659ms; Accuracy M = 89%).

Between-experiment analyses compared these findings to the results of Experiment 2 in order to determine whether the change in spatial compatibility of control reduced the advantage for targets located on the virtual limb and analyses did not reveal a significant interaction ($F(1,46) = 0.71$, $p = .40$). Analysis did, however, find a significant main effect of Target Location ($F(1,46) = 17.49$, $p = .001$) and a significant main effect of Experiment ($F(1,46) = 10.98$, $p = .002$). RT in Experiment 2 (M = 521ms) was significantly faster than in Experiment 9 (M = 647ms) and this finding is again likely to be a result of the cross control exercised over the virtual hands since the natural ipsilateral response will need to be repressed before an accurate contralateral response can be executed.

Further analysis investigated the relationship between Target Location and Finger Location to reveal a significant interaction ($F(1,23) = 5.40$, $p = .029$). As predicted by the significant on/off effect, responses by fingers located on either the inner and outer rests were faster when the target appeared on the same rest. This interaction is illustrated in Figure 15.

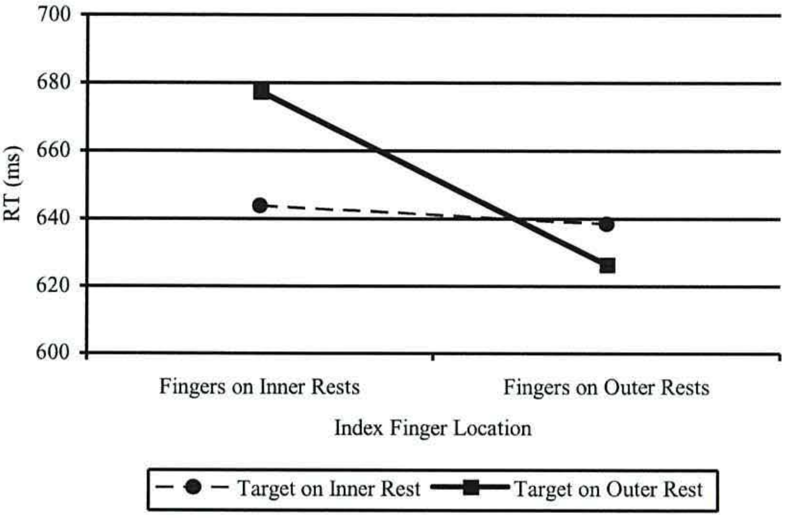

Figure 15

Mean RT (ms) as a function of Target Location and Finger Location in Experiment 9.

This experiment found that responses to a target located on a cross-controlled virtual limb were faster than responses to a target located near a cross-controlled virtual limb. These results indicate that stimuli associated with a virtual limb that is spatially incompatible with a physical limb will still receive preferential processing. This finding suggests that the association between the movements of the real and virtual hand can be specified in a flexible manner, and still result in responses biased towards the virtual limb. These findings also suggest that the on/off effect may be dependent on the virtual limbs appearing as a controllable object to be used to complete a task, since the effect is observed in the current study when the task demands state that the participant must produce movement in the virtual hand to order to respond appropriately to the target. This raises the question of whether a similar on/off effect would be observed when the participant is instructed to respond with the same-sided physical limb, rather than virtual limb, since this would render the virtual limbs irrelevant to the task at hand.

Experiment 10: Crossed Control Virtual Limbs Physical Response

Experiment 10 aimed to explore the influence of intention on the observed on/off effect. Goals and intentions are critical for successful control over an object and the manipulation of a tool will usually occur with a specific outcome in the mind of the actor.

Evidence suggests that cognitive intention can influence responses to stimuli. The Simon effect refers to reduced reaction times for trials in which there is a spatial correspondence between the stimulus location and the response, irrespective of the relevance of the stimulus location to the task demands (Simon & Small, 1969): for example, forced key choice responses to indicate the colour of a red or green light located on the right side of space will be faster with the right hand than the left hand. Riggio, Gawryszewski, and Umilta (1986) argued that this spatial compatibility is associated with the response goal rather than the anatomical location of the hand. They explored the reversed spatial compatibility effect associated with crossed hands in order to determine whether this effect was due to the crossing of the response or the crossing of the limbs. Participants were required to respond to stimuli with crossed or uncrossed index fingers and this position ensured that the hands as a whole remained in an anatomically uncrossed position in relation to the body midline throughout the experiment. Stimuli were presented to the right or left of the midline and participants were asked to respond with a same-sided key press by the appropriate index finger (for example, right sided stimuli required a right button press by the left index finger). They found that spatial compatibility was reversed in this experiment despite the fact that the hands remained uncrossed, and this finding suggests that the effect is due to the crossed response goals rather than the crossed hands.

Hommel (1993) presented further evidence to suggest that the Simon effect can be mediated by task goals or intentions. Participants were presented with a high or low tone through a left or right speaker. They were required to respond to a low tone with a left key press and a high tone with a right key press, thus the stimuli did or did not spatially correspond with the correct response (for example, a high tone in the right ear would spatially correspond with the correct response because this right-sided stimuli would require a right-sided response). Key press responses resulted in the illumination of a left- or right-sided red light. The first group of participants experienced a parallel connection between the key press response and the lights so that a right key press would result in a right-sided illumination, while the second two groups experienced inverse mapping between the responses and the lights so that a right key press would result in a left-sided illumination. Participants in the first group were instructed to 'press the left-hand key' in response to the low tone and this response resulted in an irrelevant illumination of a light on the same side of space as the response. Participants in this group exhibited a standard Simon effect with faster responses for spatially compatible stimuli. Participants in the second group were also instructed to 'press the left-hand key' in response to the low tone and this response resulted in an equally irrelevant illumination of a light on the opposite side of space as the response. Participants in this group also demonstrated the standard Simon effect, suggesting that the mapping of the responses to the consequential lights does not have a major influence on the effect. Participants in the third group, however, were instructed to 'produce the right-hand light' in response to the low tone; thus this response required the same left hand response as in the previous two conditions, but resulted in a highly relevant illumination on the opposite side of space. Participants in this condition demonstrated an inverse Simon effect: responses by the hand located on the same side as the stimuli were actually slower than responses by the hand located on the opposite side to the stimuli, and this finding suggests that the enhanced reaction times illustrated in the Simon effect are actually associated with the result of the action (illumination of the light) rather than the physical response (key press).

In Experiments 1 through 8, both the physical response (moving the real hand) and the result of the action (moving the virtual hand) involved activity in the same spatial location. Experiment 9 could dissociate between the physical response (for example, moving the right hand) and the result of the action (for example, moving the left virtual hand) because the participant had contralateral control over the virtual limbs. Experiment 9 instructed the participants to respond to the target with the same-sided virtual hand and these instructions ensured that the participant had to intentionally manipulate the virtual limbs in order to attain a specific goal. This experiment was similar to the 'produce the light' condition of the study by Hommel (1993). The results of Experiment 9 indicated a bias for stimuli associated with the virtual limbs and it was proposed that this on/off effect may be dependent on the virtual limbs appearing as a controllable tool intentionally manipulated in order to meet the goals of a task. Experiment 10 aimed to investigate this proposal by exploring whether a similar on/off effect would be observed if the control over the virtual limbs was irrelevant to the task at hand. Participants in this experiment were instructed to respond with the same-sided physical hand and, although this response again resulted in movement of the opposite virtual limb, virtual hands were described as irrelevant to the task. This experiment is similar in many respects to the 'press the key' condition in the experiment conducted by Hommel (1993). Hommel (1993) argued that the Simon effect was mediated by goal driven intentions because reduced reaction times were associated with spatial correspondence between the stimuli and the result of the action, rather than the physical action itself. Similarly, in the current experiment, the absence of an on/off effect would suggest that the bias for stimuli associated with the virtual limb is mediated by goal driven intentions because reduced reaction times are only recorded for stimuli located on a virtual limb being used to complete a task (as in Experiment 9).

Participants

Twenty-four participants (male/female ratio 4/20; aged between 18 and 45 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 10 was identical to Experiment 9, but for one crucial difference in the participant response instructions. In Experiment 10, the participant was instructed to respond to the target as quickly as possible by lifting the same-sided physical index finger, irrespective of the resultant movement in the opposite virtual finger.

Results

The data were again analysed as in Experiment 2. Analysis of RT data excluded 21.40% of trials. Mean accuracy measured at 90%. Mean RT measured at 756ms. Both error and reaction times were considerably higher in this study than in Experiment 2. This difference may be due to the fact that the participant must inhibit the urge to respond to the target with the same-sided virtual limb in order to accurately respond with the same-sided physical hand. In this experiment, the movement of the virtual limb acts as a distracter as it is irrelevant to the task at hand and this may have a negative impact on both accuracy and RT.

As in the previous experiment, analysis examined the independent variables Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger. However, in contrast to the previous experiment, analysis found that responses to a target located on a virtual finger were actually slower than responses to a target located near a virtual finger. There was a significant main effect of On/Off Finger (*F*(1,23) = 5.54, *p* = .027): responses to a target located off the finger (M = 737ms) were significantly faster than responses to a target located on the finger (M = 776ms). It was again appropriate to explore the possibility of a speed-accuracy trade-off in this experiment. Analysis did not, however, indicate any trade between speed and accuracy: performance was both faster and more accurate in the Off condition (RT M = 737ms; Accuracy M = 92%) than in the On condition (RT M = 776ms; Accuracy M = 89%).

Between-experiment analysis compared Experiment 10 with Experiment 9 to reveal a significant interaction (*F*(1,46) = 10.18, *p* = .003) showing that there is a difference between the direction of the effect observed in Experiment 9 (faster responses to targets located on the finger) and the direction of the effect observed in Experiment 10 (faster responses to targets located off the finger). Between-experiment analyses also compared Experiment 10 with Experiment 2 to reveal a similar significant interaction (*F*(1,46) = 9.60, *p* = .003) showing that there is a difference in the direction of the effects observed in Experiments 2 and 10. Further analysis comparing Experiment 2 and 10 revealed a significant main effect of Experiment (*F*(1,46) = 32.02, *p* = .001). RT in Experiment 2 (M = 521ms) was significantly faster than RT in Experiment 10 (M = 756ms). As noted above, this difference may be due to the fact that the participant must inhibit the urge to respond to the target with the same-sided virtual limb in order to accurately respond with the same-sided physical limb.

Further analysis investigating the factors Target Location, and Finger Location revealed a significant interaction (*F*(1,23) = 5.75, *p* = .025). As predicted by the reverse on/off effect, responses by fingers located on both the inner and outer rests were faster when the target appeared on a different rest. This interaction is illustrated in Figure 16.

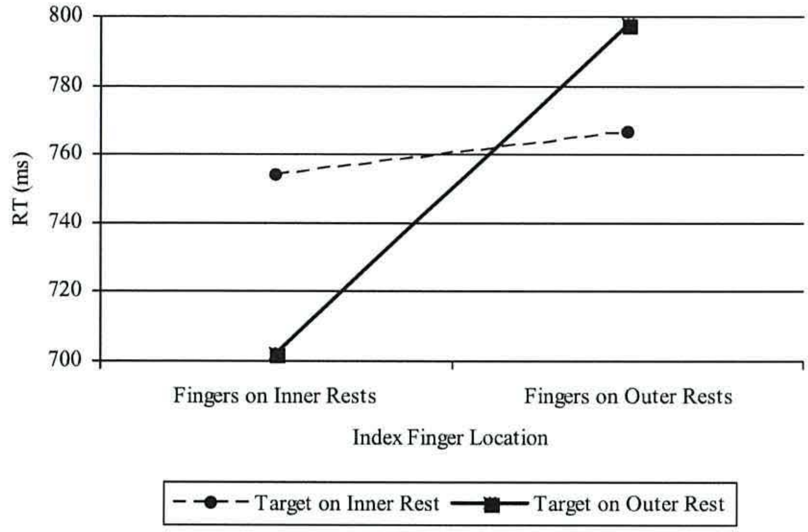

Figure 16

Mean RT (ms) as a function of Target Location and Finger Location in Experiment 10.

This experiment found that responses to a target located on the virtual limb were slower than responses to a target located near the virtual limb. This result is particularly interesting since it is in direct opposition to the results of Experiment 9, despite the fact that these two experiments were identical, but for the instructions given to the participants to respond with a virtual or real hand. This finding suggests that the direction of the on/off effect is influenced by the intention of the participant during the task.

As in previous studies, these results indicate that stimuli associated with a virtual limb under the control of a physical limb are processed differently to stimuli not associated with the virtual limbs. However, virtual limbs in this experiment were irrelevant to the task and acted primarily as a distracter to orient attention away from the spatial location of the target. It would, therefore, appear that the participant inhibited the virtual hand to the extent that responses to a target located on the hand were slower than responses to a target located near the hand. This result suggests that the exact method of control over the virtual limb is not a necessary feature, whereas the relevance of the controlled activity of the limb in relation to the task at hand is essential for responses to be biased towards the virtual limb. These findings imply that the bias for stimuli associated with the virtual limb is mediated by goal driven intentions.

Experiment 11: Virtual Limbs as Hands or Feet controlled by Feet

Experiment 11 investigated the importance of the controlling limb by placing the virtual limbs under the control of the feet. Results from the previous experiments suggest preferential processing for stimuli associated with a virtual limb under the consistent predictable control of the physical hands. These studies do not, however, determine whether this preference can be generalized to virtual limbs under the control of an alternative body part, such as the elbows or feet. Hands are typically responsible for the control of external objects and, as such, the above effect may demonstrate a specialist system for hand controlled virtual objects. The current experiment again explored the role of appearance of the virtual limbs, whilst also investigating the importance of the controlling body part by placing the virtual limbs (hands or feet) under the control of the physical feet.

Participants

Twenty-four participants (male/female ratio 6/18; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

As in previous experiments, participants were tested in a simulated 3D environment generated via an Immersive Virtual Reality System. The participant was fitted with a sensor on an adjustable plastic toe strap around the middle of each big toe in order to map a spatial correspondence between the physical movements of the participant and the visual presentation of the virtual world: movement of the feet resulted in a concurrent movement of the virtual hands/feet (see Figure 17 for photographs of the apparatus).

Figure 17

Virtual Reality Apparatus: I-visor personal display system with a lightweight 5DT sensor fixed to the front of the headset and adjustable plastic toe strap around the middle of each big toe with a lightweight 5DT sensor fixed to the top of each strap.

The stimuli and method in this experiment were similar to Experiment 2. The crucial difference in this study was that the virtual hands or feet were mapped to the physical feet of the participant and the display was located at floor-level in order to synchronise with this mapping (see Figure 18 for screenshots of the virtual environment).

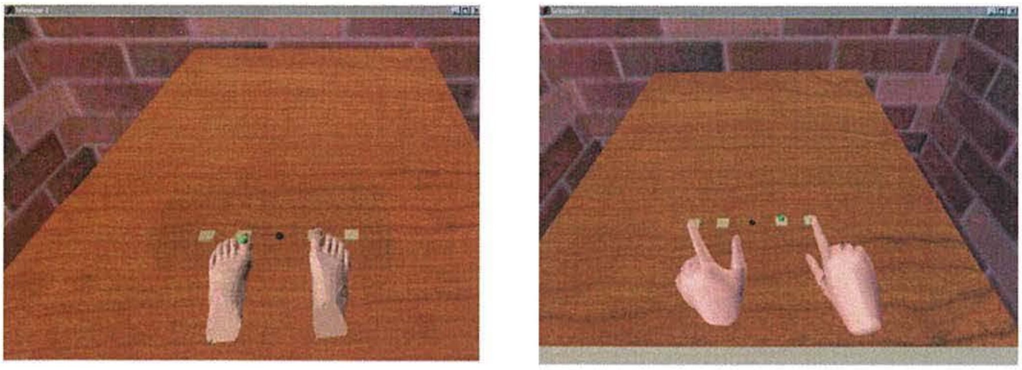

Figure 18

Screenshots of the Virtual Environment: Images from left to right illustrate the target located on the virtual feet and the target located off the virtual hands.

This experiment consisted of four blocks of 300 trials in a within-subject 2 x 2 x 2 x 2 factorial design. The independent variables in this study were the Target Side (Left or Right), Target Location (Inner Rests or Outer Rests), Limb Location (Inner Rests or Outer Rests), and Virtual Limb (Hands or Feet). Target Side and Target Location variables were again presented randomly within each block. Limb Location and

Virtual Limb variables were presented according to the block of trials (virtual index fingers rested on the inner rests for Block A and outer rests for Block B while virtual big toes rested on the inner rests for Block C and outer rests for Block D - blocks were counterbalanced between participants). The dependent variables in this study were reaction time and accuracy.

Results

The data were analysed as in Experiment 2, with the additional Virtual Limb factor. There was insufficient error data for meaningful analysis as accuracy measured at 98%. Analysis of reaction time data excluded 10.32% of trials. Mean reaction time across all conditions for all participants measured at 707ms.

This experiment again explored the independent variables Target Location and Limb Location to determine whether there was a bias towards targets located on the finger or toe. Analysis indicated a significant main effect of On/Off Limb ($F(1,23) = 15.31$, $p = .001$): responses to a target located on the limb (M = 697ms) were significantly faster than responses to a target located off the limb (M = 715ms). As illustrated in Figure 19, this effect was stronger for responses with virtual hands than for responses with virtual feet suggesting that the visual appearance of the virtual limb had some influence over the strength of the preference for stimuli associated with the virtual limb. This interaction between On/Off Limb and Virtual Limb was not, however, found to be significant ($F(1,23) = 3.02$, $p = .096$).

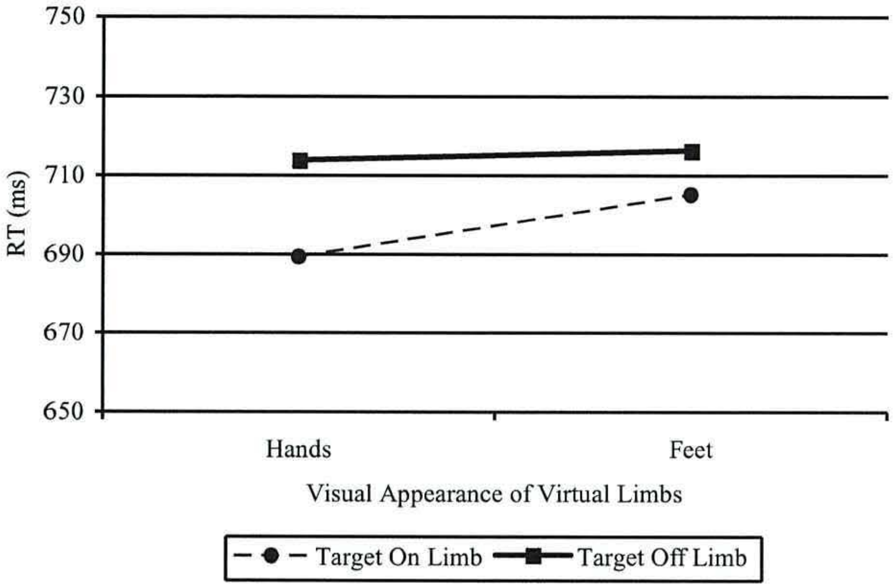

Figure 19
Mean RTs (ms) as a function of On/Off Limb and Limb Appearance in Experiment 11.

Between-experiment analyses explored the influence of limb control on the on/off effect further by comparing the findings of this experiment to the results of Experiment 2. Analyses explored the factors Experiment (Experiment 2 and Experiment 7) and On/Off Effect to reveal no significant interaction (*F*(1,46) = 0.37, *p* = .545) indicating that there is no difference between the effect observed in Experiment 2 and the effect observed in Experiment 11. Analysis did, however, reveal a significant main effect of Target Location (*F*(1,46) = 26.08, *p* = .001) and a significant main effect of Experiment (*F*(1,46) = 67.65, *p* = .001). RT in Experiment 2 (M = 521ms) was significantly faster than in Experiment 11 (M = 706ms). This finding is possibly due to the fact that responses with the feet may take longer to execute than responses with the hands (Hoffman, 1991). Please refer to Appendix 1 (Figure 33) for mean RT across all experiments.

Analysis also investigated the relationship between Target Location and Finger Location in order to further explore the on/off effect outlined above. As predicted by the observed on/off effect, results indicated a significant interaction between Target Location and Limb Location (*F*(1,23) = 13.26, *p* = .001): responses by a finger/toe located on either an inner rest or an outer rest were faster when the target appeared over the same rest. This interaction is illustrated in Figure 20.

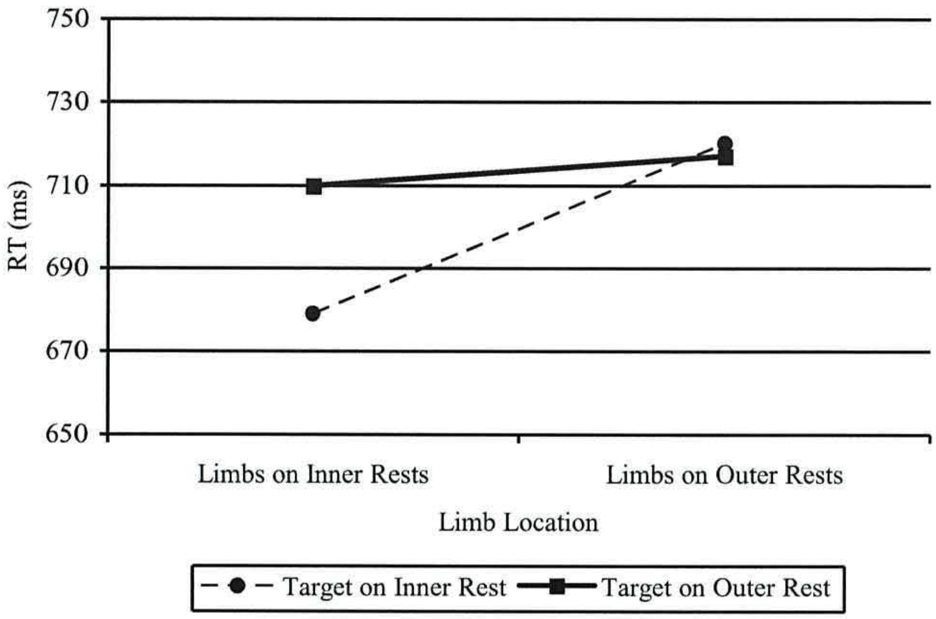

Figure 20
Mean RTs (ms) as a function of Target Location and Limb Location in Experiment 11.

Further analysis investigated the factors Target Side, Target Location, Limb Location, and Virtual Limb (Hands or Feet). Analysis revealed a significant main effect of Target Side (*F*(1,23) = 5.77, *p* = .025): responses on the left side (M = 692ms) were significantly faster than responses on the right side (M = 721ms). This finding is different to all of the previous experiments since it indicates a faster response with the left, rather than right, limb. Further investigation of the analysis reveals that this preference for the left side is restricted to the virtual feet (right M = 747ms, left M = 677ms), as the virtual hands still demonstrate a preference for the right side (right M = 695ms, left M = 708ms). This interaction between Target Side and Limb Appearance was found to be significant (*F*(1,23) = 19.17, *p* = .001). It is particularly interesting to note that the physical feet controlled both the virtual feet and the virtual hands in this experiment, thus this finding suggests that the bias for side is associated with the virtual limb rather than the physical limb. Analysis also found a significant main effect of Target Location (*F*(1,23) = 10.64, *p* = .003): responses to a target located on an inner rest (M = 700ms) were significantly faster than responses to a target located on an outer rest (M = 714ms). Further analysis revealed a significant interaction between Target Side and Target Location (*F*(1,23) = 10.08, *p* = .004): responses with the left hand were faster when the target appeared on the outer rest (M = 691ms) as opposed to the inner rest (M = 693ms), whereas responses with the right hand were faster when the target appeared on the inner rest (M = 706ms) as opposed to the outer rest (M= 736ms).

To summarise, this experiment found that responses to a target located on the virtual limb were faster than responses to a target located near the virtual limb. The previous experiments found that stimuli associated with virtual limbs under the control of the hands will receive preferential processing, and the current experiment found similar preferences for stimuli associated with a virtual limb under the control of the feet. This result highlights the similarity in processing of information associated with a foot and a hand, and Schicke and Roder (2006) offer some support for this finding. They found that similar temporal order judgment errors were recorded for both hands and feet: identification of the first point of stimulation was less accurate for crossed as opposed to uncrossed limbs, irrespective of whether the limbs were hands or feet. They concluded that response accuracy in a temporal order judgment task was independent of the limbs involved. The findings of Experiment 11 suggest that responses can be biased toward a virtual limb under the control of an alternative body part (feet in this experiment, but could possibly be generalized to include elbows or knees for amputee patients – further research should be conducted to explore these possibilities).

Experiment 12: Virtual Limbs with Tools controlled by Tools

Experiment 12 investigated the potential for 'second-hand' control by placing virtual objects under the control of a physical tool wielded by the participant. Results from the previous experiments suggest preferential processing for stimuli associated with an object under the 'direct' control of the participant (movement of the physical hand results in movement of the virtual hand). These studies do not, however, determine whether this preference can be generalized to objects under 'indirect' or 'second-hand' control (movement of the physical hand manipulates the movement of a physical tool which results in movement of a virtual object). This issue of indirect control is highly relevant to the tool and equipment industry. Individuals are often required to respond to stimuli with a tool rather than their own body in order to successfully interact with a specific aspect of the environment. For example, a tennis player is required to control a racket to respond to the ball because it would be impractical (and rather painful) for the tennis player to interact directly with the ball. Similarly, a builder is required to control a screwdriver in order to manipulate a screw because it would be extremely difficult to turn the screw directly with fingers. Indirect control is also somewhat relevant to the prosthetic industry since amputee patients will use an artificial limb in order to interact with the world. It is essential that amputee patients adapt to respond to stimuli associated with this artificial limb in the same way as they respond to stimuli associated with a real limb so it is important to determine whether a bias can be observed in response to stimuli associated with a virtual object under the control of a non-body part. In other words, if an amputee patient completed this experiment using artificial limbs rather than actual limbs, would the patient indicate a bias towards the virtual limb under the control of their prosthetic in the same way that participants exhibit a bias for virtual limbs under the control of a real hand? This experiment explored the importance of 'direct', as opposed to 'indirect' or 'second-hand', control by placing the virtual objects (imitation of hands holding tools) under the control of the participant via the manipulation of a physical tool.

Participants

Twenty-four participants (male/female ratio 7/17; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

As in the previous experiment, participants were tested in a simulated 3D environment. The participant was asked to hold one plastic tool in each hand: tools were white plastic sticks measuring approximately 8cm in width and 30cm in length (see Figure 21 for photographs of the apparatus). Each tool was fitted with a sensor in order to map a spatial correspondence between the physical movements of the participant and the visual presentation of the virtual world: movement of a hand holding a tool resulted in a concurrent movement of a virtual hand holding a virtual tool.

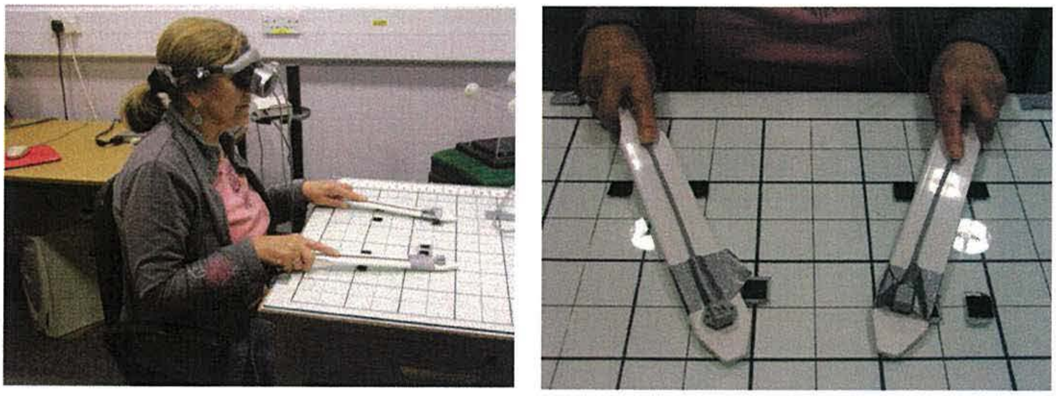

Figure 21

Virtual Reality Apparatus: I-visor personal display system with a lightweight 5DT sensor fixed to the front of the headset fitted over the head and white plastic tool with a lightweight 5DT sensor fixed to the tip held in each hand.

Stimuli and method were again similar to Experiment 2 with the crucial difference that the physical tools held in the hands of the participant were mapped to a pair of virtual tools held by virtual hands in the simulation. The participant was required to activate the rests by placing the tips of the virtual tools on the tool rest squares and the target appeared on one of the rests (either on or off the tips of the virtual tools). Participants were instructed to respond to the target by lifting the same-sided tool. Please refer to Figure 22 for screenshots of the virtual environment.

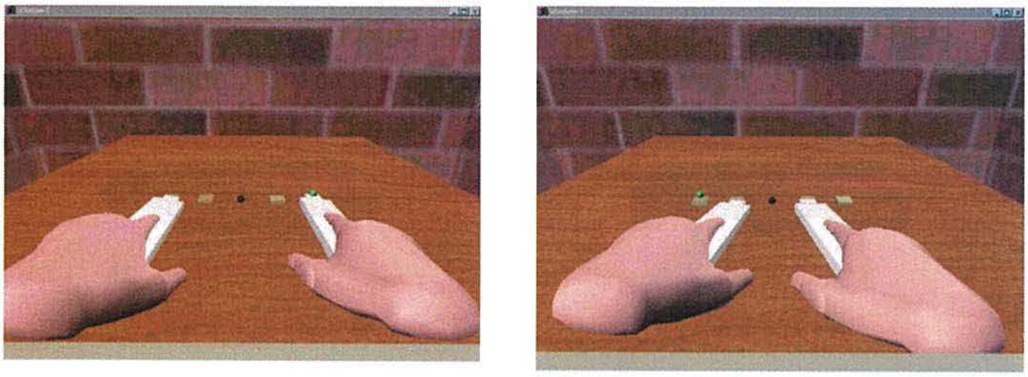

Figure 22

Screenshots of the Virtual Environment: Images from left to right illustrate the target located on the virtual tool and the target located off the virtual tool.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent and dependent variables in this study were the same as the variables in Experiment 2.

Results

The data were analysed as in Experiment 2. There was insufficient error data for meaningful analysis as accuracy measured at 99%. Analysis of reaction time data excluded 8.95% of trials. Mean reaction time across all conditions for all participants measured at 655ms.

As in previous studies, the primary focus of this experiment was to determine any differences in response to targets located on versus off the virtual tool by examining the independent variables Target Location and Tool Location. This analysis indicated a significant main effect of On/Off Tool ($F(1,23) = 6.96$, $p = .015$): responses to a target located on a tool (M = 649ms) were significantly faster than responses to a target located off a tool (M = 661ms).

Between-experiment analyses compared the findings of this experiment to the results of Experiment 2 in order to determine whether the change in control reduced the advantage for targets located on the object. Analyses did not reveal a significant interaction ($F(1,46) = 0.07$, $p = .79$) suggesting that there is no significant difference between the effect observed in Experiment 2 and the effect observed in Experiment 12. Further analysis revealed a significant main effect of Target Location ($F(1,46) = 17.20$, $p = .001$) and Experiment ($F(1,46) = 41.94$, $p = .001$). RT in Experiment 2 (M = 521ms) was significantly faster than in Experiment 12 (M = 655ms). This finding is possibly due to the additional weight of the tool slowing the responses in the current experiment.

Analysis investigated the relationship between Target Location and Tool Location in order to further explore the on/off effect. As predicted by the observed effect, analysis found a significant interaction ($F(1,23) = 6.89$, $p = .015$). However, although responses by a tool located on an inner rest were faster when the target appeared over the same rest, responses by a tool located on an outer rest were actually faster when the target appeared over a different rest. This interaction is illustrated in Figure 23.

This finding was unusual, as the on/off effect was not observed for tools situated on an outer rest. It is important to acknowledge, however, that the interaction is significant thus the overall pattern of results still lends support to the suggestion that responses are slightly more biased towards stimuli located on the virtual feet.

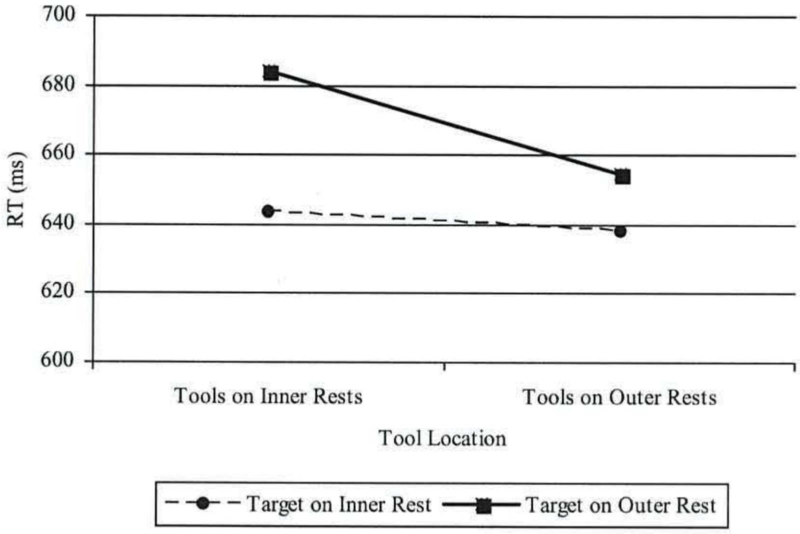

Figure 23
Mean RT (ms) as a function of Target Location and Tool Location in Experiment 12.

Further analysis investigated the factors Target Side, Target Location, and Tool Location to reveal a significant main effect of Target Side (*F*(1,23) = 17.59, *p* = .001): responses on the right side (M = 629ms) were significantly faster than responses on the left side (M = 681ms); and a significant main effect of Target Location (*F*(1,23) = 17.59, *p* = .001): responses to a target located on an inner rest (M = 641ms) were significantly faster than responses to a target located on an outer rest (M = 669ms). Analysis also indicated a significant interaction between Target Side and Target Location (*F*(1,23) = 5.25, *p* = .031): responses by the right and left tools were faster when the target appeared on the inner rest as opposed to the outer rest, although this difference was greatest for responses on the right. Additional analysis revealed a significant three-way interaction between Target Side, Target Location, and Tool Location (*F*(1,23) = 6.79, *p* = .016).

In summary, this experiment found that responses to a target located on a virtual tool controlled by a physical tool were faster than responses to a target located near the virtual tool. These results indicate that stimuli associated with a virtual tool under the control of a physical tool can receive preferential processing. This finding suggests that the nature of controllability is flexible to the extent that virtual objects under 'second-hand' control (virtual object under the control of a physical tool, which is in turn under the control of the individual) can also result in bias. This finding is highly relevant to the tool and equipment industry and somewhat relevant to the prosthetic industry because it suggests that an individual could demonstrate a similar preference for stimuli associated with an object such as a tool or prosthetic limb as they exhibit for stimuli associated with their own body.

Conclusion

Experiments completed in the previous chapters found that responses to a target located on a virtual limb are faster than responses to a target located near the virtual limb, irrespective of the visual appearance, spatial orientation, and spatial location of the limb. Experiments described in this chapter highlight the role of control as a mediating factor in this effect: preferential processing of stimuli located on, as opposed to near, the virtual limb was dependent on the individual wielding consistent predictable control over the virtual limb. The findings of these experiments suggest that control over virtual limbs can result in enhanced processing for stimuli associated with the virtual limbs.

Experiments 7 and 8 explored the role of control and predictability to investigate the possibility of perceptual or control based accounts of the bias for stimuli located on the virtual limbs. These experiments provided participants with a perceptually identical environment to Experiment 2, with only the control over the virtual limbs differing from this baseline study. The findings of these experiments suggest that the participant is not simply biased towards moving objects, but rather demonstrates a specific response bias for stimuli located on objects under predictable control.

While these experiments indicate that it is essential for the participant to exercise predictable control over the virtual limbs for preferential processing of associated stimuli (Experiments 7 and 8), it would appear that the exact nature of control over the limbs might be specified in a flexible manner. Experiment 9 recorded reduced reaction times in response to targets located on virtual limbs under the control of the opposite limb, Experiment 11 observed reduced reaction times in response to targets located on a virtual limb under the control of the physical feet, and Experiment 12 found reduced reaction times in response to targets located on a virtual tool under the control of a physical tool. These studies suggest that the bias towards stimuli associated with the virtual limbs will remain irrespective of the type of controlling limb, provided that this limb can consistently and predictably control the action of the virtual limb. The findings of Experiments 9 and 10 also suggest that this effect is mediated by goal driven intentions, implying that the bias for stimuli associated with the virtual limbs is dependent on the intentional use of the virtual limbs as tools to meet the goals of a task. Furthermore, Experiment 10 suggests that the mapping between the controlling limb and the virtual limb is robust to the extent that virtual limbs irrelevant to the task will be inhibited resulting in increased reaction time responses to stimuli associated with these objects.

The six experiments described in this chapter were compared with Experiment 2 to reveal significant differences in overall mean reaction times for those experiments in which the participant had predictable control over the virtual limb: Experiments 9, 10, 11, and 12 were each found to record slower reaction times than Experiment 2. It was interesting to note, however, that Experiments 7 and 8 did not record significantly different reaction times to Experiment 2, and this finding highlights the perceptual and design similarities between these three studies. Additional findings revealed a consistent bias for responses to targets located on the right side of fixation in Experiments 7, 8, and 12, although this bias was switched to the left side when the virtual limbs were presented as feet in Experiment 11. Experiments 9 and 10 did not indicate a significant preference for the right side of fixation, although this is likely to be due to the cross control nature of the study. Analysis also revealed a bias for targets presented on the inner rests in Experiments 7, 8, 11, and 12, and this finding suggests that participants respond faster to targets located closer to fixation. Other findings were observed during analysis, although exploration of the results did not indicate any findings consistent across numerous experiments or relevant to the main hypothesis of the study. Please refer to Appendix 2 and 3 for comparison of the on/off effect between experiments and Appendix 4 for comparison of all other observed effects.

As noted in Chapter 4, some of the results of the previous experiments appeared inconsistent with the findings of research exploring the concept of 'ownership'. Pavani and Castiello (2003) noted that the incorporation of a hand shadow into personal space is subject to the visual appearance of the shadow: dressing the physical hand in a misshapen glove in order to distort the shadow can eliminate the effect observed in this study. Similarly, there is evidence to suggest that the rubber hand illusion may also be dependent on the visual appearance of the hand: replacing the rubber hand with a wooden stick, stroking the right rubber hand and left physical hand, or presenting the rubber hand at a different angle to the physical hand can all significantly reduce the effect of the illusion (Farne, Pavani, Menghello, & Ladavas, 2000; Pavani, Spence, & Driver, 2000; Tsakiris & Haggard, 2005). All of these findings suggest that the preferential processing of stimuli associated with the virtual limbs should be dependent on numerous visual and spatial factors. Experiments 3 to 6, however, observed preferential processing of stimuli associated with virtual limbs irrespective of the visual appearance, spatial orientation, and spatial location of the limbs. The findings of Experiments 7 to 12 suggest that this discrepancy could be directly related to the issue of control: control over the movement of the virtual hands was essential for the completion of the task whereas control over the movement of the shadow/rubber hand was not permitted in the research described above (Farne, Pavani, Menghello, & Ladavas, 2000; Pavani & Castiello, 2003; Pavani, Spence, & Driver, 2000; Tsakiris & Haggard, 2005). The current research suggests that a wide variety of objects can be incorporated into body schema and personal space if control over the object is present and predictable. In the absence of control, other factors, such as visual appearance and spatial proximity, may then become more important. This conclusion is consistent with recent findings in the rubber hand research (Azanon & Soto-Faraco, 2007; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005), which suggest that the understanding of the body schema and personal space is heavily dependent on control over the body.

In addition to visual appearance, tactile feedback is another factor that may become extremely important in the absence of control. The findings of the present research suggest that there is a bias for stimuli associated with any object under the control of the individual. It is important to consider, however, any conditions under which it may be possible for the individual to experience a bias for stimuli associated with an uncontrollable object. Control over the body is often closely related to the experience of tactile feedback since sensory feedback and control will usually exist simultaneously. It is true that an individual may be able to exercise control over a tool without experiencing any form of tactile feedback directly from the object (for example, tennis players can control a racket but they do not experience sensation in the strings). It is also true that an individual may be able to experience tactile feedback without being able to control a particular part of the body (for example, a restrained hand cannot be moved to complete a task but the individual will still experience sensation from the skin). With regards to the body, however, complete restrictions on movement are not common (even a restrained hand can often be moved to some extent - perhaps wiggling the fingers or flexing the wrist) and it is usually the case that the individual will experience both control over the limb and tactile feedback from the limb. Indeed, paralysis will often result in impairment in the experience of sensation in the body, and it would be fairly unusual for a patient to be able to exercise complete control over a part of the body without experiencing any tactile feedback from that region. It may, therefore, be speculated that sensory feedback will lead to the natural assumption that the object is likely to be under control, irrespective of actual evidence of command over the object. For this reason, it may be proposed that there could be a marginal bias toward stimuli associated with an object not under the control of the individual, provided that the individual has experienced prior sensory feedback from the object.

Chapter 6

Role of Visuo-Tactile Sensation in the bias towards the Virtual Limbs

Experiments completed in the earlier chapters found that responses to a target located on a virtual limb under the control of the individual are faster than responses to a target located near the virtual limb, irrespective of the visual appearance, spatial orientation, and spatial location of the limb. Experiments conducted in the previous chapter highlight the role of control as a mediating factor in this effect: preferential processing of stimuli located on, as opposed to near, the virtual limb was dependent on the individual wielding consistent predictable control over the limb. It was noted in the previous chapter, however, that the experience of control is often closely related to the experience of tactile feedback and both of these factors may play a part in the creation of a body schema and the definition of personal space boundaries. It was speculated in the conclusion to that chapter that the sensory experience of feedback from the virtual limb may even reinstate the bias for stimuli located on the virtual hands in the absence of control.

Research in this area tends to focus on the issue of control with reference to a sense of agency and the experience of tactile feedback with reference to a sense of ownership. Ownership has been defined as an awareness of an action or a sensation experienced by your own body, whereas agency is defined as an awareness of your control over an action performed by your own body (Gallagher, 2003). Evidence suggests that both the sense of agency and the sense of ownership are equally crucial for a complete psychological concept of self. Indeed, Vignemont, Tsakiris, and Haggard (2006) emphasise the importance of integrating a sense of agency and a sense of ownership in order to establish a unified representation of the body.

However, as discussed in Chapter 5, there are several theoretical concerns associated with the use of these terms. Ownership is often regarded as a subjective concept, as the awareness of a limb as a part of your own body and the awareness of tactile sensation applied to this limb is personal to the sensing subject (Bermudez, 1998). It is, of course, acknowledged that another individual may be able to observe the limb being touched or detect whether the skin on the limb feels hot or cold; but only the sensing subject is able to offer a complete analysis of the tactile sensation from a personal perspective. Investigation of the sense of ownership must, therefore, rely on the self-report of the participant. This method is understandably inappropriate since it is open to a wide variety of potential confounds. Rubber hand research has attempted to develop an alternative method for measuring the extent to which the participant will assume ownership of an external object. Botvinick and Cohen (1998) instructed participants to indicate the location of their physical hand following synchronous tactile stimulation of the viewed rubber hand and hidden physical hand. This design allows an objective measure of the perceptual drift of the real hand towards the rubber hand and it is assumed that this displacement indicates a sense of ownership since those participants who reported an illusory sensation in the rubber hand would also displace the location of the real hand. Whilst these assumptions may remain somewhat controversial, one can at least appreciate how this design demonstrates an association between tactile stimulation of the real hand and visual stimulation of the rubber hand. Experiment 13 will adopt this method in a simulated environment in order to explore the influence of stimulation of the real hand and virtual hand on the subsequent estimated location of the real limb. However, in order to avoid any speculative debate about the subjective experience of the participant, this experiment will focus on the objective exposure to tactile and/or visual stimulation, rather than referring to the invocation of a sense of ownership. Experiments 14 and 15 will further explore the effect of concurrent stimulation of the real and virtual hands on the bias for stimuli located on the virtual limbs.

Experiment 13: Distance Judgement following Physical and/or Visual Sensation

Experiment 13 investigated the estimated location of the real hands following concurrent stimulation of the real and virtual limbs. Botvinick and Cohen (1998) found that participants who reported the rubber hand illusion (feeling as though the rubber hand was their own hand after synchronous stroking of the real and fake limb) would also displace the location of their real hand towards the rubber hand. The current experiment adapted this measure of displacement now common to rubber hand research by comparing estimates of the location of the physical hand before and after an experience of physical and/or visual activity in a virtual environment.

Participants

Sixty participants (male/female ratio 20/40; aged between 18 and 45 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Participants were seated before a table containing a long rule to the left of the midline and a blue box to the right of the midline (see Figure 24 for photographs of the apparatus). The participant was required to rest their left hand on their lap and place their right hand inside the box on the table: this hand was positioned with the index finger extended so that the tip made contact with the tabletop 12cms from the edge of the table. The participant was instructed to guess the location of the fingertip by imagining a line drawn across the table from the tip of the finger on the right to a rule located down the left side. The experimenter continually reminded the participant to remain stationary during the estimate. This first distance judgment was recorded to be compared with the later estimate.

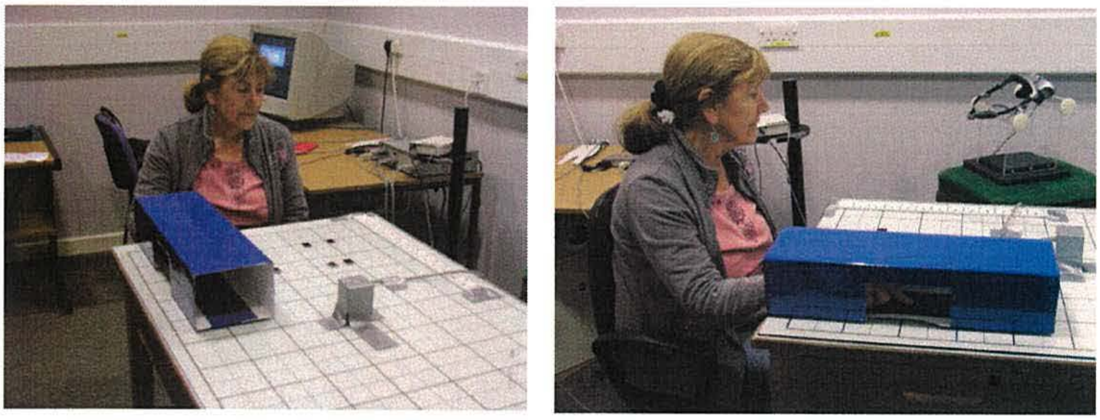

Figure 24

Distance Judgment Apparatus: The blue box hid the right hand of the participant from view (side section was removed to allow the experimenter to stroke the physical hand) and there was a rule running along the left side of the table in order to allow the participant to make distance judgments.

Participants then experienced an activity in a simulated 3D environment. Inside the virtual world, one virtual hand was mapped to the real hand of the participant and one virtual hand was mapped to the real hand of the experimenter. These virtual hands were displaced approximately 50cm in front of the participant. The participant was again asked to place their right hand inside the box so that the tip of the index finger was positioned 12cm from the edge of the table. Participants were informed that their hand could be in the same or a different location to the previous test: in reality, the hand was positioned in the same location for both tests. Participants were asked to fix their eyes on their own virtual hand to experience the activity for approximately 30 seconds. Activities varied according to the experimental condition. Stroke conditions required the participant to experience the virtual hand and/or physical hand being stroked by the experimenter: physical and visual condition allowed the participant to feel their physical hand being stroked while observing their virtual hand being stroked; physical only condition allowed the participant to feel their physical hand being stroked while the virtual hand remained unaffected; visual only condition allowed the participant to observe their virtual hand being stroked while the physical hand remained untouched (see Figure 25 for a screenshot of a stroke condition). Tap conditions required the participant to experience the virtual hand and/or physical hand being tapped: physical and visual condition allowed the participant to tap their physical hand while observing the matched movement in the virtual hand; physical only condition allowed the participant to tap their physical hand while their virtual hand remained stationary; visual only conditions allowed the participant to observe their virtual hand tapping while their physical hand remained stationary (see Figure 25 for a screenshot of a tap condition). Participants were required to remain stationary after the virtual experience while the headset was removed by the experimenter. Participants were repeatedly reminded to keep their right hand immobile inside the box.

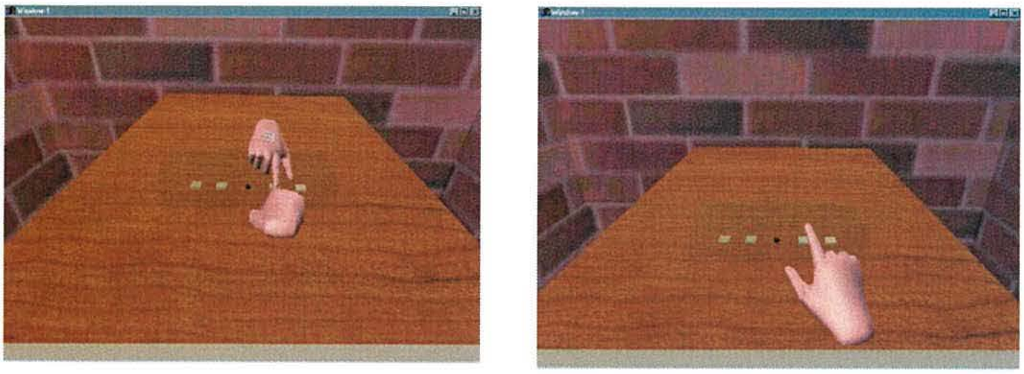

Figure 25

Screenshots of the Virtual Environment: Images from left to right illustrate the virtual hand during the Stroke condition and the virtual hand during the Tap condition.

Participants were then asked to make their second distance judgment. The participant was again instructed to guess the location of the finger tip by imagining a line drawn across the table from the tip of the finger to the rule. The second distance judgment was recorded to conclude the experiment.

This experiment adopted a 2 x 3 between-subject design testing ten participants in each condition. The independent variables in this study were Stimulation (Stroke or Tap) and Feedback (Physical and Visual or Physical Only or Visual Only). The dependent variable in this study was the difference in centimeters between the first and second distance judgment.

Results

Distance judgments obtained after the activity (second estimate) were subtracted from distance judgments obtained before the activity (first estimate) in order to ascertain the difference in centimetres. Differences (cm) were subjected to descriptive (mean) and inferential (ANOVA) statistical analysis. Mean estimates across all conditions for judgments after the activity were 13.28cm and mean estimates across all conditions for judgments before the activity were 13.13cm. The average difference between the two distance judgements across all conditions was 0.15cm.

Analysis investigated the factors Stimulation and Feedback. Analysis revealed a significant main effect of Feedback ($F(5,55) = 8.38$, $p = .001$). As illustrated in Figure 26, differences were considerably greater and directionally different for dual modality physical and visual feedback (M = 0.95cm) than for single modality physical only feedback (M = -0.25cm) and visual only feedback (M = -0.2cm). Further consideration of this data reveals that this large difference was consistent for dual modality feedback in both stroke conditions (M = 0.8cm) and tap conditions (M = 1.1cm).

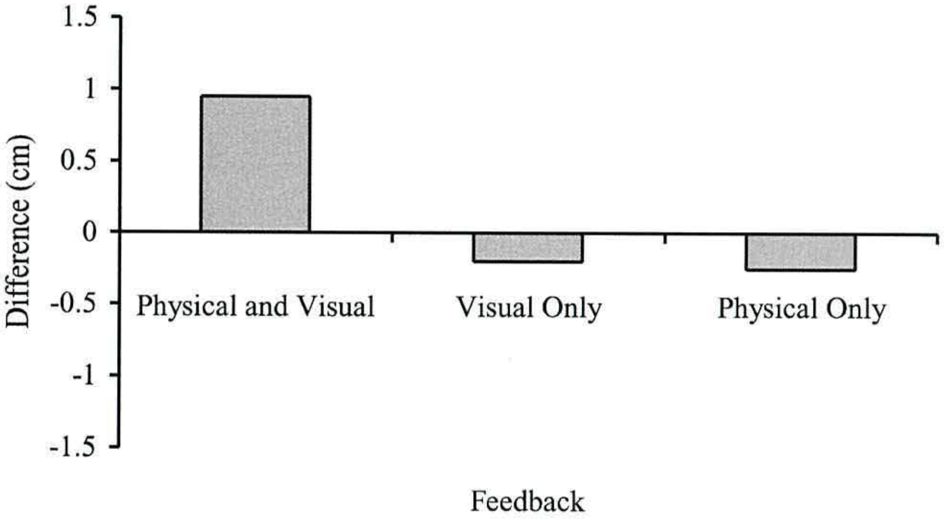

Figure 26
Mean Difference (cm) as a function of Feedback in Experiment 13.

Descriptive analysis of distance estimates before and after the activity reveal that the second estimate was greater than the first estimate following dual modality activities, whereas the second estimate was less than or equal to the first estimate following single modality activities. Distance estimates before and after each activity are illustrated in Figure 27.

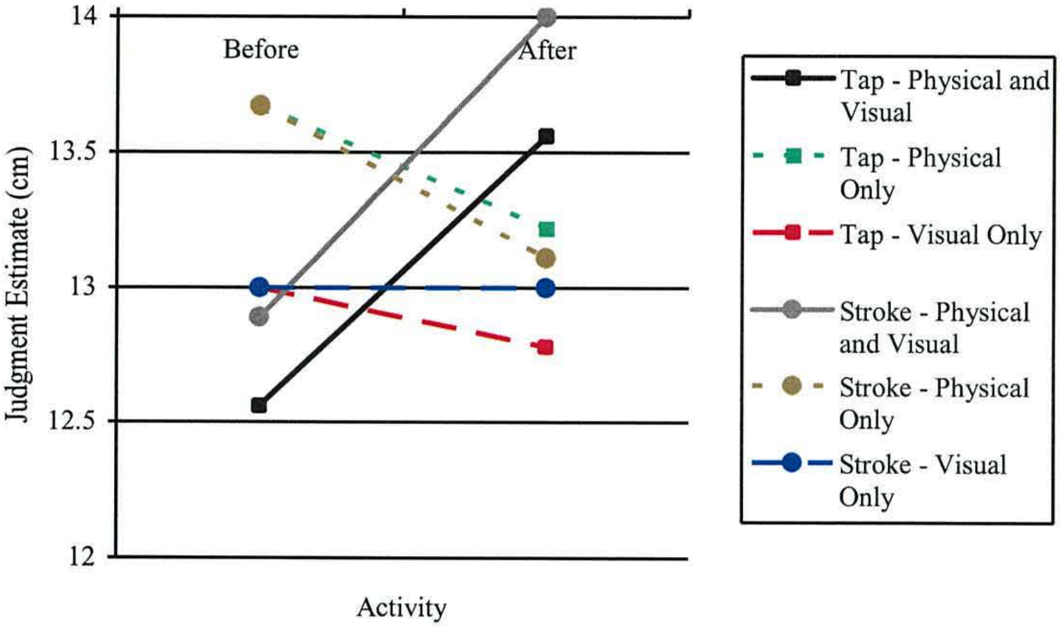

Figure 27

Mean Distance Judgments (cm) before and after activity as a function of Stimulation / Feedback in Experiment 13.

This experiment found that exposure to an activity involving a virtual hand displaced 50cm in front of the physical hand could influence a subsequent estimation of physical hand location: dual modality (visual and physical) activities resulted in enhanced estimations of distance, whereas single modality (visual or physical) activities resulted in equivalent estimations of distance.

An additional control study was conducted in order to determine whether the second distance judgement would be greater, less than, or equivalent to the first judgement in the absence of activity. Ten naïve participants (male/female ratio 2/8; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested using the same method as above, with the crucial difference that the activity was to watch the stationary virtual hand while counting aloud to thirty. This experiment found that the second distance judgment (M = 12.7cm) was less than the first distance judgment (M = 13.2cm). These results indicate that the perceived location of the physical hand was displaced towards the body following basic exposure to the virtual limb in the absence of any specific interaction on a sensory level. This finding suggests that single modality activities have the same effect as basic exposure to the virtual limb for thirty seconds, whereas dual modality activities have a distinct influence on the estimation of physical hand location.

The results of this experiment suggest that a rubber hand type illusion can be induced with a virtual limb in response to concurrent sensory and visual feedback. Furthermore, subjective reports from the participants indicate that the virtual hands 'felt' like their own limbs after concurrent sensory and visual feedback. On the basis of the assumptions established in the rubber hand research, this finding suggests that the participant can experience the illusion of sensation from the displaced virtual limb under certain circumstances (synchronous visual and tactile sensation).

Experiment 14: Visual/Tactile Feedback from Immobile Virtual Limbs

Experiment 14 investigated the effect of visual and tactile feedback on subsequent responses to stimuli located on or near the immobile virtual limbs. Experiment 7 did not find a preference for stimuli associated with a virtual limb that is not under the control of the participant. Experiment 13, however, suggests that tactile sensation can appear to stem from the virtual limbs as a result of synchronous stroking of both the physical and virtual hands, and it is possible that this sensory experience may reinstate the preference for stimuli associated with immobile virtual limbs. Experiment 14 explores this possibility by inducing a visual and tactile experience associated with the immobile virtual limbs prior to the replication of Experiment 7.

Participants

Twenty-four participants (male/female ratio 8/16; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 14 adopted the same design, apparatus, and stimuli as Experiment 7. The crucial difference in this study was the pre-experiment experience of concurrent stimulation of the virtual and physical hand. Participants were instructed to position their physical hands to mimic the position of the virtual hands on the table.

Participants were then required to watch each extended virtual index finger being stroked by the virtual finger of the experimenter while experiencing concurrent strokes along each of their physical index fingers (see Figure 28 for screenshots of the virtual hands being stroked). This stroking activity was completed for sixty seconds per hand prior to each block of trials.

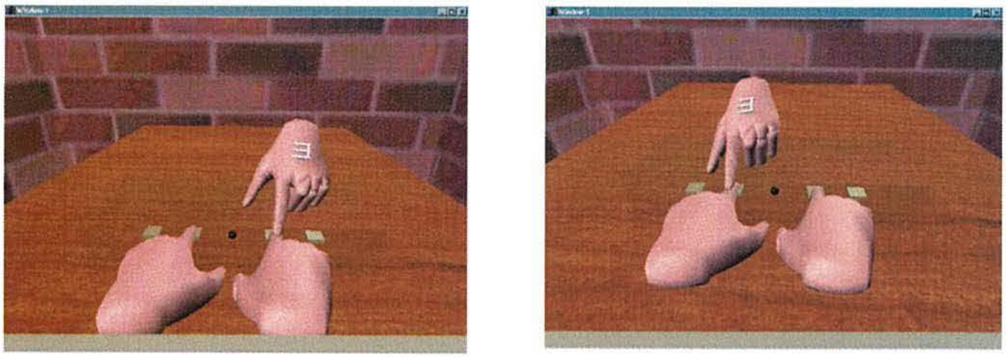

Figure 28
Screenshots of the Virtual Environment: Images from left to right illustrate the right virtual hand being stroked and the left virtual hand being stroked.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design. The independent and dependent variables in this study were the same as Experiment 7.

Results

The data were analysed as in Experiment 7. There was insufficient error data for meaningful analysis as accuracy measured at 99%. Analysis of reaction time data excluded 7.4% of trials. Mean reaction time across all conditions for all participants measured at 575ms. Please refer to Appendix 1 (Figure 33) for mean RT across all experiments.

As in Experiment 7, the focus of this study was to determine any differences in response to targets located on versus off the virtual limb. This analysis was completed by examining the independent variables Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger. Analysis indicated that there was a significant main effect of On/Off Finger (*F*(1,23)

= 8.91, *p* = .001): responses to a target located on the finger (M = 572ms) were significantly faster than responses to a target located off the finger (M = 577ms).

Between-experiment analysis compared the findings of Experiment 14 with Experiment 7 in order to determine whether the experience of tactile feedback reinstated the advantage for targets located on the immobile limbs. Analysis explored the factors Experiment (Experiment 2 and Experiment 7) and On/Off Effect (Target On Limb and Target Off Limb): significant interaction between these two factors would suggest that the on/off effect observed in Experiment 14 is significantly different from the absence of the on/off effect observed in Experiment 7. Analysis did not reveal a significant interaction (*F*(1,46) = 4.05, *p* = .050), although the level of probability was close to significant and further analysis revealed that the level of power could have been too low to detect a true difference (power = .5). This finding suggests that there may be some marginal differences between Experiment 7 and Experiment 14, even though this difference does not reach statistical significance. This is supported by the descriptive analysis indicating that there is no on/off effect (0ms difference between on and off) in Experiment 7 and a significant on/off effect (5ms difference between on and off) in Experiment 14. It could, therefore, be argued that the visual/tactile feedback did have a marginal, although insignificant, effect on the bias for stimuli associated with the immobile limbs.

As in all of the previous experiments in this thesis, between-experiment analyses also compared the findings of the current experiment with Experiment 2. This comparison was completed in order to determine whether the absence of control following visual/tactile stimulation influenced the advantage for targets located on the limbs. Analysis explored the factors Experiment (Experiment 2 and Experiment 14) and On/Off Effect (Target On Limb and Target Off Limb): significant interaction between these two factors would suggest that the on/off effect observed in Experiment 14 is significantly different to the on/off effect observed in Experiment 2. This analysis did not reveal a significant interaction (*F* (1,46) = 3.83, *p* = .056) suggesting that there is no difference between the on/off effect observed in the current experiment and the on/off effect observed in Experiment 2.

Between-experiment analysis of Experiments 2 and 14 also revealed a significant main effect of Experiment (*F*(1,46) = 9.33, *p* = .004): RT in Experiment 2 (M =

521ms) was significantly faster than in Experiment 14 (M = 575ms). Similarly, between-experiment analysis of Experiments 7 and 14 revealed a significant main effect of Experiment (*F*(1,46) = 7.11, *p* = .011): RT in Experiment 7 (M = 530ms) was significantly faster than in Experiment 14 (M = 575ms). Analysis in the previous chapter revealed that there were no differences in RT between Experiment 2 and Experiment 7 and it was noted that this similarity in reaction times highlights the similarities in the visual presentation of these two experiments. It is interesting to note that RT in Experiment 14 was considerably slower than in both of these previous experiments; yet the visual presentation of this experiment was again identical, except for the pre-experiment visual/tactile experience. This finding suggests that the visual/tactile activity associated with the virtual limbs did have an effect on the overall responses to the targets. Perhaps one has an expectation of control after the experience of sensation apparently deriving from the virtual limbs (caused through concurrent visual and tactile stimulation of virtual and physical hands) and this conflict between tactile feedback from the virtual limbs and the unexpected absence of control results in confusion, as illustrated by the slower reaction times?

As anticipated by the on/off effect, further analysis of Experiment 14 indicated a significant interaction between Target Location and Finger Location (*F*(1,23) = 8.70, *p* = .007). However, although responses by a tool located on an inner rest were faster when the target appeared over the same rest, responses by a tool located on an outer rest were actually faster when the target appeared over a different rest. This interaction is illustrated in Figure 29. This finding was unusual, as the on/off effect was not observed for tools situated on an outer rest. It is important to acknowledge, however, that the interaction is significant thus the overall pattern of results still lends support to the suggestion that responses are slightly more biased towards stimuli located on the virtual feet.

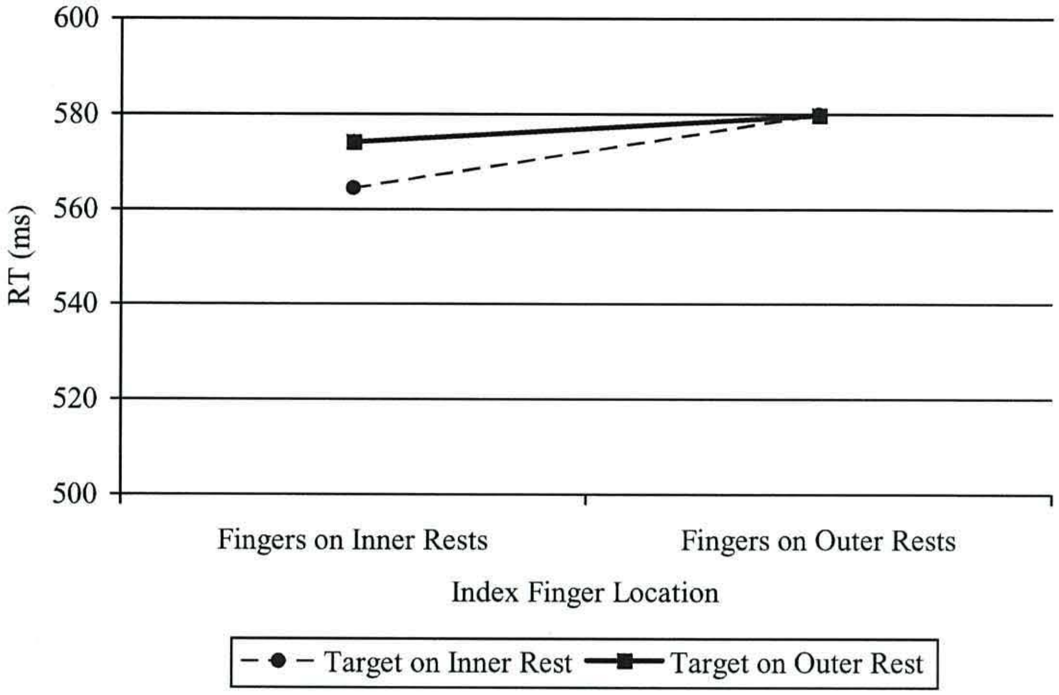

Figure 29
Mean RT (ms) as a function of Target Location and Finger Location.

Further analysis of Experiment 14 investigated the factors Target Side, Target Location, and Finger Location in order to identify any other noteworthy main effects or interactions. Analysis revealed a significant main effect of Target Side (*F*(1,23) = 29.27, *p* = .001): responses by the right hand (M = 562ms) were significantly faster than responses by the left hand (M = 587ms).

This experiment found that responses to a target located on a virtual limb were faster than responses to a target located near a virtual limb. These results indicate that stimuli associated with immobile virtual limbs can receive preferential processing under certain circumstances. This finding suggests that the visual/tactile feedback resulted in subsequent enhanced processing of stimuli associated with the virtual limbs. These results cannot, however, eliminate the possibility that the experience of watching any type of activity involving the virtual limbs may have acted as a cue to direct attention towards the virtual limbs. It was therefore necessary to conduct an additional control study designed to investigate responses to stimuli located on or near an immobile virtual limb following only the visual experience of the virtual hands being stroked.

Experiment 15: Visual Feedback from Immobile Virtual Limbs

Experiment 15 investigated the effect of visual feedback on subsequent responses to stimuli located on or near the immobile virtual limbs. Experiment 14 recorded a preference for stimuli associated with immobile virtual limbs following concurrent stroking of the physical and virtual hands. Experiment 15 will explore the possibility that the bias towards immobile virtual limbs can be reinstated through visual only feedback by exposing the participant to visual stroking of the virtual hands prior to the replication of Experiment 7.

Participants

Twenty-four participants (male/female ratio 9/15; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 15 was identical to Experiment 14, except for the fact that the physical hands did not receive any stimulation so that the participant experienced only visual feedback. This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 factorial design and the independent and dependent variables were the same as in the previous study.

Results

The data were analysed as in Experiment 7. There was insufficient error data for meaningful analysis as accuracy measured at 99%. Analysis of reaction time data excluded 8.53% of trials. Mean reaction time across all conditions for all participants measured at 580ms.

As in the previous experiment, this study aimed to determine any difference in response to targets located on versus off the virtual limb. However, in contrast to previous experiment, analysis indicated that there was no significant main effect of On/Off Finger ($F(1,23) = 0.26$, $p = .618$). Responses to a target located on the finger (M = 579ms) were not significantly faster than responses to a target located off the finger (M = 581ms). This finding suggests that the bias for targets located on the immobile limbs cannot be reinstated through the experience of visual feedback only.

Between-experiment analysis compared the findings of Experiment 14 and Experiment 15 to determine whether the type of feedback delivered prior to the task influenced the subsequent on/off effect. Experiment 14 provided the participant with concurrent visual and tactile feedback prior to the task and the results of this study indicated a significant on/off effect. Experiment 15 provided the participant with visual feedback only prior to the task and the results of this study did not reveal a significant on/off effect. Analyses investigated the factors Experiment (Experiment 14 and Experiment 15) and On/Off Effect (Target On Limb and Target Off Limb) in order to explore whether the type of feedback influenced the bias towards stimuli associated with immobile virtual limbs: significant interaction between these two factors would suggest that the on/off effect observed in Experiment 14 is significantly different to the absence of the on/off effect observed in Experiment 15. This analysis did not reveal a significant interaction ($F(1,46) = 0.38$, $p = .541$). However, power analysis revealed that the level of power could have been too low to detect a true difference (power = .09) thus it is possible that these findings would have been different if more participants had been tested. On the basis of the current findings, it can only be suggested that a significant on/off effect was observed in Experiment 14 whereas no significant on/off effect was observed in Experiment 15, although the findings of each of these studies were not found to be significantly different.

As in all of the previous experiments in this thesis, between-experiment analyses also compared the findings of the current experiment with Experiment 2. This comparison was completed in order to determine whether the absence of control following visual only stimulation influenced the advantage for targets located on the limbs. Significant interaction between Experiment (Experiment 2 and Experiment 15) and On/Off Effect (Target On Limb and Target Off Limb) would suggest that the on/off effect observed in Experiment 2 is significantly different to the absence of the on/off effect observed in Experiment 15. This analysis did not reveal a significant interaction (*F* (1,46) = 3.82, *p* = .056) suggesting that there is no difference between the results of the current experiment and the on/off effect observed in Experiment 2. However, power analysis revealed that the level of power could have been too low to detect a true difference (power = .48) and descriptive analysis did reveal some interesting differences between Experiments 2 and 15: the significant difference between on and off effect in Experiment 2 measured 14ms whereas the non-significant difference between on and off in Experiment 14 was only 2ms. This finding suggests that the effect observed in Experiment 2 may be impaired by the absence of control, despite the visual feedback delivered prior to the task. Between-participant analysis of Experiment 2 and Experiment 15 also revealed significant main effects of Target (*F*(1,46) = 7.12, *p* = .010) and Experiment (*F*(1,46) = 17.11, *p* = .001). RT in Experiment 2 (M = 521ms) was significantly faster than in Experiment 15 (M = 580ms)

Further analysis investigated the factors Target Side, Target Location, and Finger Location. Analysis did not reveal any significant main effects. Analysis did, however, indicate a significant interaction between Target Side and Target Location (*F*(1,23) = 13.02, *p* = .001): responses by the left hand were faster when the target appeared on the inner rest (M = 580ms) as opposed to the outer rest (M = 590ms), whereas responses by the right hand were faster when the target appeared on the outer rest (M = 574ms) as opposed to the inner rest (M = 577ms), although the difference for the right hand was greater than the difference for the left hand. Analysis also indicated a significant three-way interaction between Target Side, Target Location, and Finger Location (*F*(1,23) = 9.13, *p* = .006).

This experiment found that responses to a target located on an immobile virtual limb were not faster than responses to a target located near an immobile virtual limb, despite prior experience of visual stimulation of the virtual limb. This result suggests that the effect observed in Experiment 14 was not simply the result of attention being directed towards the virtual hands through activity: it would appear that the preference for stimuli located on, as opposed to near, a pair of uncontrollable virtual limbs can be reinstated through concurrent visual and tactile stimulation, but cannot be reinstated through visual stimulation alone. This finding suggests that control and/or concurrent visual and tactile feedback associated with a virtual limb are necessary factors for a bias towards the virtual limb.

Conclusion

Experiments completed in the previous chapters found that responses to a target located on a virtual limb under the control of the individual are faster than responses to a target located near the virtual limb, irrespective of the visual appearance, spatial orientation, and spatial location of the limb. Experiments described in this chapter investigated the role of tactile sensation as a mediating factor in this effect: initial studies aimed to determine whether tactile sensation can be associated with virtual hands and subsequent studies aimed to determine whether this experience could invoke preferential processing of stimuli associated with the virtual hands in the absence of control.

Rubber hand research suggests that synchronous tactile stimulation of the viewed rubber hand and hidden physical hand can result in an association between real and rubber hands to the extent that the rubber hand begins to 'feel' like a real hand and estimation of the location of the real hand is displaced towards the rubber hand (Botvinick & Cohen, 1998). The results of the experiments reported in this chapter suggest that a rubber hand type illusion can be invoked for a virtual limb: Experiment 13 found that the estimated location of the real hand was displaced towards the distant virtual hand following synchronous visual feedback from the virtual hand and tactile feedback from the real hand.

Previous experiments suggested there is a bias for stimuli associated with any object under the control of the individual. It was noted in the previous chapter, however, that there could be some conditions under which it may be possible for the individual to experience a bias for stimuli associated with an uncontrollable object. Prior research has highlighted tactile feedback as a crucial component of the body schema and control over the body is often closely related to the experience of tactile feedback since tactile feedback and control will usually exist simultaneously. It was speculated that tactile feedback could lead to the natural assumption that an object is likely to be under control, irrespective of actual evidence of command over the object. For this reason, it was proposed that there could be a marginal bias toward stimuli associated with a virtual object not under the control of the individual, provided that the individual has experienced prior tactile feedback from the object.

Experiments 14 and 15 replicated the design of Experiment 7 by ensuring that the virtual hands remained immobile throughout the trials. The crucial difference in these studies, however, was the pre-experiment experience of visual and tactile feedback (Experiment 14) or visual only feedback (Experiment 15). The results of these experiments revealed a significant on/off effect in Experiment 14 when the participant was provided with concurrent visual and tactile feedback from the virtual limbs. This finding suggests that the bias towards stimuli associated with an immobile virtual limb can be reinstated by the experience of tactile sensation appearing to emanate from the virtual limb (similar to the rubber hand illusion). These results did not, however, reveal a significant on/off effect in Experiment 15 when the participant was provided with visual feedback only. This finding suggests that the bias for targets associated with immobile virtual limbs cannot be reinstated by visual stimulation alone.

Between-experiment comparisons explored the findings of Experiments 2 and 7 conducted in previous chapters with Experiments 14 and 15 conducted in the current chapter. The findings of each of these individual experiments seem to support the suggestion that control is important for the on/off effect, but tactile feedback can reinstate the effect to some extent in the absence of control (Experiment 2: control / no tactile feedback = on/off effect; Experiment 14: no control / tactile feedback = on/off effect; Experiments 7 and 15: no control / no tactile feedback = no on/off effect). Statistical analysis of the comparisons between these experiments, however, do not reveal any significant difference between the on/off effect observed in Experiment 14 and the absence of the effect observed in Experiment 15. Analysis also failed to find a significant difference between the effect observed in Experiment 14 and the absence of the effect in Experiment 7. Similarly, analysis failed to find a significant difference between the effect observed in Experiment 2 and the absence of the effect in Experiment 15. It can be concluded from all of these findings that both the visuo-tactile feedback (Experiment 14) and the visual only feedback (Experiment 15) had a similar impact on the on/off effect in terms of direction; however, the visual only feedback did not have sufficient impact to reinstate the on/off effect, whereas the visuo-tactile feedback was able to reinstate the on/off effect. These findings can be taken as tentative evidence to suggest that responses can be biased towards stimuli located on an uncontrollable limb following visuo-tactile feedback from the limb, although additional research is needed in this area in order to further explore the strength of this bias following independent visual and tactile feedback.

To summarise the research completed in this thesis thus far, Experiments 1 to 15 have investigated the on/off effect observed by Hari and Jousmaki (1996) in order to identify those features that are necessary to elicit a bias for stimuli located on the limbs. Hari and Jousmaki (1996) noted that reaction times were faster in response to stimuli located on a hand, and Experiments 1 and 2 revealed a similar bias for stimuli associated with a virtual limb. Experiments 3 to 6 found that the visual appearance and spatial location of the virtual limb did not influence the on/off effect as the bias remained for virtual mirror hands, feet, and cones. Experiments 9, 11, and 12 found that the method of control over the virtual limbs did not influence the on/off effect as the bias remained for limbs under the control of the opposite hands, feet, and tools. The on/off effect was, however, impaired by the absence of predictable and intentional control over the limbs to complete a specific task in Experiments 7, 8, and 10. However, Experiments 14 and 15 in the current chapter revealed that responses could be biased towards a virtual limb in the absence of control, provided that there has been prior experience of visuo-tactile feedback from the virtual limbs. Further research is needed in this area in order to determine whether the bias for immobile limbs can only be reinstated by concurrent visual and tactile feedback, or whether the bias can also be reinstated by visual feedback alone. All of the experiments reported thus far in this thesis have explored the nature of the on/off effect and the findings of these studies have provided a considerable body of evidence to demonstrate the conditions under which an on/off effect is most likely to be observed.

Chapter 7

Attention Bias or Compatibility Effect

Experiments completed in the previous chapters found that responses to a target located on a virtual limb under the intentional and predictable control of the individual were faster than responses to a target located near the virtual limb, irrespective of the visual appearance, spatial orientation, and spatial location of the limb. These experiments explored the nature of the on/off effect to indicate the optimal conditions for the preference for targets associated with the virtual limbs. These experiments did not, however, explore the underlying cause of this effect. There are two potential explanations for the observed bias in responses to stimuli located on the virtual limb: response bias may illustrate a compatibility effect or an attention bias towards the body.

Compatibility Effect related to the Body

Relationships between a stimulus and a response are regarded as compatible if the association proceeds to facilitate or enhance the response in some respect. Kornblum, Hasbroucq, and Osman (1990) argued that compatibility can often be observed when a stimulus is either matched or, more commonly, mapped to a specific response. Compatibility as a result of stimulus-response matching will occur when a stimulus is the same as the subsequent response in some respect: responses matched to identical stimuli (compatible matching) will be more efficient than responses matched to opposite or different stimuli (inverse or incompatible matching) (Fitts & Deininger, 1954). For example, depression of a green button in response to a green light will be completed faster than depression of a red button. Similarly, compatibility as a result of stimulus-response mapping will occur when a stimulus occupies the same spatial field as the response: responses mapped to stimuli located in the same spatial field (compatible mapping) will be more efficient than responses mapped to stimuli located in the opposite spatial field (inverse or incompatible mapping) (Fitts & Seeger, 1953). For example, responses to a light target presented on the right side of space will be completed faster by the right hand than the left hand. Stimulus-response compatibility may be assumed to illustrate our natural inclination to respond in a particular manner to certain types of stimuli or stimuli situated in a certain location.

Further evidence to suggest a natural or automatic response linked to specific types of stimuli has been presented in studies exploring stimulus-response correspondence. Unlike compatibility effects, stimulus-response correspondence can be observed when an association between a task-irrelevant stimulus and a response will proceed to facilitate action. In these studies, enhanced responses do not appear to be dependent on the relevance of the mapping or matching to the task. The Simon effect is proposed to demonstrate a form of stimulus-response correspondence in which the mapping between the location of the stimulus and the location of the response is entirely irrelevant to the task demands, yet corresponding responses are still recorded as faster than non-corresponding responses (Simon & Small, 1969). For example, forced key choice responses to indicate the colour of a red or green light located on the right side of space will be faster with the right hand than the left hand. Simon (1969) argued that stimuli are automatically coded with regards to location and suggested that this effect illustrates our 'natural tendency to respond towards the source of stimulation' (Simon, 1969, p174).

Similar natural tendencies may be proposed to exist with regards to the body. One might assume that responses paired with stimuli associated with the body will be more compatible, easier to form, and faster to process, than responses paired with stimuli not associated with the body. This would appear to be logical from an evolutionary perspective since automatic coding of stimuli located on the body resulting in enhanced processing and responses to these stimuli would certainly aid survival: consider the seemingly natural inclination to shake the hand if it is suspected that a potentially dangerous insect may have landed on the skin.

Findings presented by Hari and Jousmaki (1996) could be interpreted to support the suggestion that there is a compatibility effect in operation for stimuli associated with the body and responses made by the body. Hari and Jousmaki (1996) found that responses to stimuli located on the body were faster than responses to stimuli located near the body and concluded that these findings were the result of a stimulus-response compatibility effect. They proposed that motor programs will be activated faster by stimuli located on the body itself because stimuli situated beyond the body will require an additional processing step designed to determine the location of the stimuli from a body-centred perspective. Although this conclusion has been criticised in subsequent research by Whiteley, Kennett, Taylor-Clarke, and Haggard (2004) (for details please refer below to the final paragraph of the 'Attention Bias towards the Body'), the bias towards the virtual body observed in the experiments in the previous chapters could also be explained in terms of a stimulus-response compatibility effect. Stimuli located on the virtual limbs may be processed faster than stimuli located off the virtual limbs because the response action (lifting same-sided virtual limb) is compatible with the stimulus (target located on same-sided limb).

Attention Bias towards the Body

Selective attention to stimuli in the visual field can be biased towards objects of a certain appearance and/or objects occupying a specific spatial location. Attention can be temporarily biased towards stimuli as a result of task demands: target detection tasks requiring the participant to respond to an object of a particular shape or colour will bias attention towards stimuli with these features whereas cueing tasks directing the participant to a specific region of space will bias attention towards stimuli in this spatial location. Attention may also be biased towards stimuli deemed a threat or aid to survival: evolutionary forces may bias attention towards stimuli with potentially dangerous features, such as venom, and stimuli with potentially beneficial features, such as food. Similarly, it would also appear logical to suggest that attention may be biased towards stimuli associated with the physical body of the individual.

Attention evolved in conjunction with motor activity in order to ensure successful interaction between the organism and the environment (Tipper, Lortie, & Baylis, 1992) and it could therefore be predicted that a cooperative relationship will exist between action and attention. Traditional study of the relationship between action and attention has adopted a feed-forward approach emphasising the influence of visual attention on the efficiency of motor activity; however, recent study of this relationship has adopted a bi-directional perspective suggesting that motor activity may have an influence over the allocation of attention in the same way that attention can have an influence on motor performance.

The premotor model of attention has presented an account of the dynamic relationship between action and attention. This model proposes that a motor program is designed prior to the initiation of any activity and subsequent allocation of attention is restricted to the pattern specified by this program, irrespective of whether the actual motor activity is executed. Rizzolatti, Riggio, Dascola, and Umilta (1987) found that responses to a target at a cued location were significantly faster than responses to a target at an uncued location and the cost of a response to a target at an uncued location was positively correlated with the distance between the target and the cued location. Rizzolatti et al (1987) argued that the cost of responding to a target at an uncued location is the consequence of an essential correction in the established motor program. The ocular motor program for the movement of attention from fixation to the target was established on the basis of the cue and additional time must be taken to correct this program in response to the presentation of the target at the uncued location.

Research to support the premotor modal of attention has noted evidence of improved visual attention in cases of enhanced motor activity and worsened visual attention in cases of impaired motor activity. Deubel and Schneider (1996) found that a saccade in the direction of a target significantly enhanced subsequent target detection. Deubel, Schneider, and Paprotta (1998) found that a manual reaching movement in the direction of a spatially distinct object significantly impaired subsequent target detection. Posner, Cohen, and Rafal (1982) observed congruent attention and motor deficits in patients with progressive supranuclear palsy and noted that those unable to execute horizontal eye movements demonstrated a concurrent failure to orient attention in the horizontal dimension.

Research in the field of clinical neuropsychology has provided further evidence to illustrate the influence of motor activity on visual attention. Heilman and Watson (1977), Heilman and Valenstein (1979), and Heilman, Watson, and Valenstein (1993) argued that hemispatial neglect is a consequence of a disruption in attention mechanisms resulting in a failure to attend to stimuli located in the contralesional hemispace. Hemispatial neglect has been attributed to damage of the cortical and subcortical circuits responsible for the coding of space for the control of motor activity (Rizzolatti & Berti, 1993; Rizzolatti & Camardi, 1987). There is a considerable body of evidence to suggest that the deliberate activation of a contralesional limb can significantly enhance attention to stimuli located in the neglected hemispace. Joanette, Brouchon, Gauthier, and Samson (1986) found that patients suffering left hemispatial neglect demonstrated enhanced detection of contralesional stimuli when the contralateral hand completed the task. Joanette et al (1986) suggested that attention in the left visual field was enhanced as a result of increased activation in the right hemisphere due to activity by the left limb and concluded that the presentation of neglect may differ in accordance with the laterality of the motor response. Halligan, Manning, and Marshall (1991) found that neglect patients demonstrated fewer line bisection errors when the response was initiated from the left visual field irrespective of the laterality of the responding hand. Halligan et al (1991) argued that the effect of limb activation on neglect may be a result of spatio-motor cueing and concluded that any motor activity in the neglect hemifield will reduce neglect for contralesional stimuli.

Brown, Walker, Gray, and Findley (1999) provided evidence for the reduction of neglect as a result of arbitrary activity of the contralesional limb. Neglect patients often demonstrate marked difficulties in reading and may fail to read one half of each word or omit words from one half of the page. Two neglect patients were asked to read six passages of text aloud before, during, and after limb activation. Limb activation consisted of the operation of a pedal switch on the foot of the first participant and the operation of a tilt switch on the wrist of the second participant. This study revealed a significant reduction in word omissions from the left side of the page during and after the activation of the left limb. Furthermore, it was observed that this reduction in extinction severity was maintained for a number of minutes after the completion of the limb activation. Brown et al (1999) concluded that overt voluntary orienting of attention towards neglected space is improved by any activation of a contralesional limb.

Robertson and North (1992, 1993, 1994) further investigated limb activation effects in a series of studies to determine the influence of task irrelevant limb activation on visual neglect. They found that the patient demonstrated improved letter cancellation during concurrent activation of the left hand or the left leg in left hemispace. Robertson and North (1992) applied these findings to the general arousal theory, the proprioceptive cueing theory, the visual cueing theory, the spatio-motor cueing theory, and the recruitment theory. General arousal was discounted as an explanation for the limb activation effect since concurrent movement of the left limb and the right limb in their respective hemifields did not result in a significant reduction in neglect. Proprioceptive cueing was discounted as an explanation since passive movement of the left limb by the experimenter did not result in a significant reduction in neglect. Visual cueing was discounted as an explanation for the limb activation effect since the improvement in neglect was observed when the left arm was concealed from view and the improvement was not observed following attempts to 'find' their left arm or read a clock located in left hemispace. Spatio-motor cueing was also discounted as an explanation for the effect since the improvement in neglect was not observed following activation of the right limb in the left hemifield. Recruitment of the perception system in the right hemisphere as a result of the activation of the motor system in the right hemisphere was discounted as an explanation for this effect since the activation of the left limb in the right hemifield did not result in a significant reduction in neglect. Additional evidence has also discounted the theory that the limb activation effect is a consequence of increased foveal activity in the neglected field since contralesional limb activity resulted in a reduction in visual extinction in the absence of increased saccades (Mattingley, Robertson, & Driver, 1998). Robertson and North (1994) noted that the limb activation effect is observed only during active movement of the left limb in the left hemifield and they concluded that this effect is the result of a lower perceptual threshold for attention in the neglected field due to simultaneous activation of personal space (movement of the left limb) and reaching space (movement in left hemifield). These findings suggest that motor activity can result in enhanced attention to the region of space around the active limb and this evidence would further support the theory that there is a specific attention system responsible for stimuli located close to the body.

Further evidence to suggest that attention is biased towards the body has been presented by Reed, Grubb, and Steele (2006). They found that participants demonstrated enhanced target detection when they placed one hand near the target location. This effect appeared to indicate a specific bias towards the body rather than a general directing of attention since additional experiments did not reveal a similar preference for targets appearing near a visual anchor of the same size. Further experiments revealed that this preference for targets located near the hand is not related to cue validity or the shifting of spatial attention. Reed et al (2006) concluded these findings demonstrate an attentional prioritization of space associated with the hand.

Research to date has provided compelling data to support the theory that there is a specific attention system responsible for stimuli located in the region of space surrounding the body. Findings presented by Hari and Jousmaki (1996) could be interpreted to support the suggestion that attention is biased towards the body itself. Hari and Jousmaki (1996) found that responses to stimuli located on the body were faster than responses to stimuli located near the body. As noted in the previous section, Hari and Jousmaki concluded that their findings illustrated a type of stimulus-response compatibility effect. An alternative interpretation of their findings, however, could suggest that this result was due to an attention bias towards the body. This interpretation has received additional support in a replication of their study conducted by Whiteley, Kennett, Taylor-Clarke, and Haggard (2004). In this replication, participants were required to respond to a target located on their actual finger or a finger shaped block by executing a forced choice key press with the concealed right hand. They found significantly faster reaction times in response to a target located on the index finger of the participant relative to a target located on the neutral finger-shaped block. They attributed these results to an attention bias toward stimuli located on the body because this experiment eliminated the possibility of a compatibility effect by requiring the participant to make a forced choice key press with their hidden right hand. Experiments completed in the previous chapters found that responses to stimuli located on the virtual body were faster than responses to stimuli located near the virtual body and this finding could also be the result of an attention bias towards the body.

Compatibility vs Attention

Research suggests that reduced reaction times in response to stimuli located on the virtual hand may be due to a compatibility effect or an attention bias. The experiments described in the previous chapters aimed to explore the nature of the on/off effect. These studies were not designed to distinguish between these two potential explanations and the effect observed in these studies could be explained equally well through the compatibility effect explanation or the attention bias explanation. It is noted, however, that the method adopted in these experiments could be adapted to differentiate between compatibility and attention based explanations. Compatibility effects require a direct relationship between a stimulus and a response (lifting same-sided hand in response to a target), whereas an attention bias can still be illustrated through an intermediate symbol (discriminating between two letter targets with a key press). Enhanced accuracy in the discrimination of a letter located on, as opposed to near, a virtual limb would eliminate the possibility that the observed response bias is the result of a compatibility effect. Experiments 16 and 17 will measure accuracy in response to a letter presented on or near the virtual limb: Experiment 16 will require the participant to identify the letter by lifting the left or right limb and Experiment 17 will require the participant to identify the letter by touching a key in the virtual world.

Experiment 16: Letter Discrimination Task – Hand Lift Response

Experiment 16 investigated the accuracy of letter detection responses to a target located on or near the virtual hands. Previous experiments found faster responses to stimuli associated with the virtual limbs. Experiment 16 explored the possible causes of this effect. This experiment aimed to distinguish between a stimulus-response compatibility explanation and an attention bias explanation by replicating the method of Experiment 2, but asking the participants to identify a target letter located on or near the virtual limb by lifting the left or right limb, rather than responding with the same-sided limb. Enhanced accuracy for stimuli located on the body would suggest an attention bias, as this finding could not be explained through a simple stimulus-response compatibility account.

Participants

Twenty-four participants (male/female ratio 7/17; aged between 18 and 35 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 16 utilized the same apparatus and stimuli as previous experiments. The crucial difference in the stimuli for this experiment was that the participants were presented with a visual target in the form of a green letter L or T over an inner or outer finger rest to the left or right of fixation after the trial had been initiated (see Figure 30 for screenshots of the virtual environment). This experiment also adopted a similar design to previous studies with participants required to respond to the target as quickly as possible by lifting an index finger from the finger rest. However, participants in this experiment were instructed to respond with the left index finger if the target was the letter L and the right index finger if the target was the letter T.

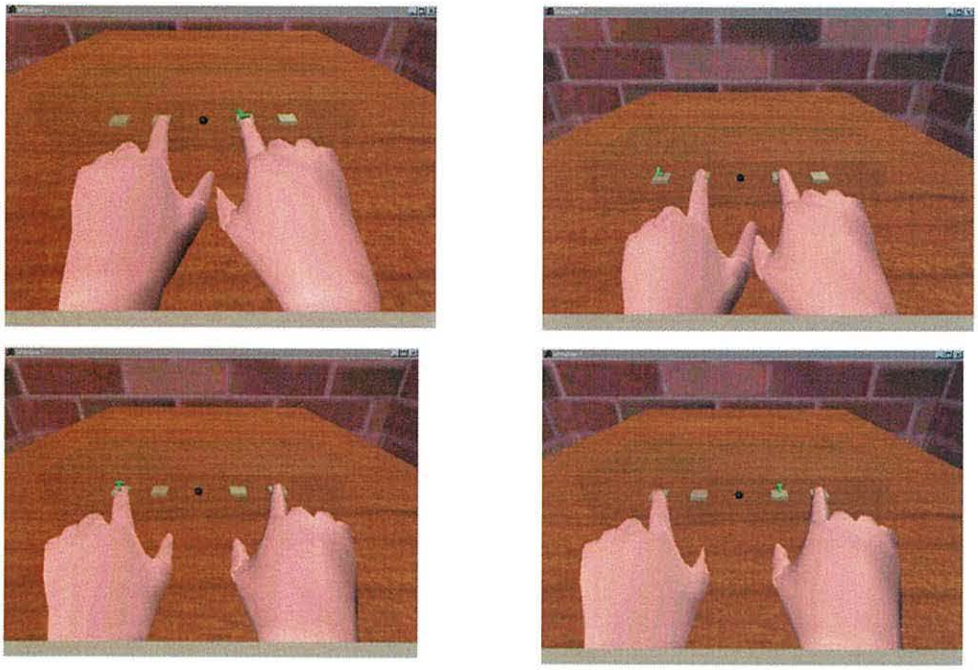

Figure 30

Screenshots of the Virtual Environment: Images by row from left to right illustrate the L target located on the virtual limb, L target located off the virtual limb, T target located on the virtual limb, and T target located off the virtual limb.

This experiment consisted of two blocks of 300 trials in a within-subject 2 x 2 x 2 x 2 factorial design. The independent variables in this study were the Target (L or T), Target Side (Left or Right), Target Location (Inner Rests or Outer Rests), and Finger Location (Inner Rests or Outer Rests). As in previous experiments, Target Side and Target Location variables were presented randomly within each block along with Target, while the Finger Location variable was presented according to the block of trials. The dependent variables in this study were accuracy and reaction times.

Results

The data were analysed as in Experiment 2, although the analysis for this experiment focused more on accuracy than previous studies in order to dissociate between stimulus-response compatibility and attention bias accounts.

Mean accuracy measured 96%. The primary focus of this experiment was to determine any difference in accuracy for responses to targets located on versus off the virtual limb. This analysis was completed by examining the independent variables Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger. Analysis did not reveal a significant main effect of On/Off Finger ($F(1,23) = 4.18$, $p = .053$): responses to a target located on the finger (M = 95%) were not significantly different to the responses to a target located off the finger (M = 96%). Further analysis investigated the factors Target, Target Side, Target Location, and Finger Location. Analysis did not reveal any interactions, although it did reveal a significant main effect of Target Location ($F(1,23) = 4.46$, $p = .046$): responses to targets located over the inner rest (M = 96%) were significantly more accurate than responses to targets located over the outer rest (M = 95%). This finding suggests that accuracy was enhanced for targets located closer to fixation.

Mean RT measured at 823ms. Analysis of the on/off effect was again completed by examining the independent variables Target Location and Finger Location in terms of whether the target was located on the virtual finger or near the virtual finger. Analysis did not find a significant main effect of On/Off Finger ($F(1,23) = .13$, $p = .724$). Further analysis of the factors Target, Target Side, Target Location, and Finger Location revealed a significant main effect of Target Location ($F(1,23) = 28.39$, $p = .001$): responses to targets located over the inner rest (M = 797ms) were significantly faster than responses to targets located over the outer rest (M = 849ms). This effect has been observed in several of the previous experiments and is supported by the results of the accuracy data. This finding may be assumed to indicate a preference for targets located closer to fixation.

This experiment found that there was no difference in accuracy or RT for responses to a target located on a virtual limb and responses to a target located near a virtual limb. Accuracy in this experiment was, however, consistently high and the difference between responses to targets located on and off the virtual hands accounted for only 1%. It could be argued that accuracy in this experiment had reached a ceiling level thus any responses recorded could not accurately reflect differences between the two conditions. These results are, therefore, inconclusive and cannot discriminate between the compatibility effect explanation and the attention bias explanation.

Experiment 17: Letter Discrimination Task – Key Touch Response

Experiment 16 failed to differentiate between the stimulus-response compatibility explanation and the attention bias explanation for the on/off effect. Experiment 17 attempted to dissociate between these two explanations by replicating the previous experiment with increased task difficulty. This experiment required the participants to make a forced choice key press by touching a virtual key to identify a briefly presented letter. Enhanced accuracy for stimuli located on the body would suggest an attention bias, as this finding could not be explained through a stimulus-response compatibility account.

Participants

Twenty-four participants (male/female ratio 8/16; aged between 18 and 45 years; right-handed; normal or corrected vision) were tested in this experiment.

Method

Experiment 17 used similar apparatus and stimuli to previous experiments. In this experiment, however, two corresponding reach squares were located directly above the hand rests and the independent activation of each rest was indicated by a colour change from white to red (see Figure 31 for screenshots of the virtual environment). Activation of both hand rests would initiate each trial and, immediately after the initiation of a trial, one hand rest and corresponding reach square would change from red to green. The participant was instructed to respond to this colour change as quickly as possible by moving the appropriate hand from the green rest to the green reach square.

One visual target appeared for a set time period on the back of a virtual hand or on the table between the two rests during this hand movement. The visual target was in the form of a black upright or inverted letter L or T. The duration of exposure to the target varied between 10ms and 1000ms in accordance with the accuracy of the previous response. A correct response resulted in a decrease in the duration of exposure to the target: exposure decreased by 25ms if the previous exposure had been less than 100ms, exposure decreased by 50ms if the previous exposure had been between 100ms and 250ms, and exposure decreased by 100ms if the previous exposure had been greater than 250ms. An incorrect response resulted in an increase in the duration of exposure to the target: exposure increased by 100ms if the previous exposure had been less than 100ms, exposure increased by 50ms if the previous exposure had been between 100ms and 250ms, and exposure increased by 25ms if the previous exposure had been greater than 250ms. Minimum threshold of the duration was 10ms and maximum threshold of duration was 1000ms. Duration of the exposure was recorded in order to assess the difficulty of the task.

Two letter identification keys materialized at either side of the hand after the completion of the movement from the hand rest to the corresponding reach square. The participant was required to indicate the observed letter irrespective of the letter orientation (upright or inverted) and responses to the letter were completed by touching one of the letter identification keys: activation of the key to the right indicated the letter T and activation of the key to the left indicated the letter L. Letter identification keys disappeared in response to activation through contact with a virtual hand. Accuracy was recorded to conclude the trial.

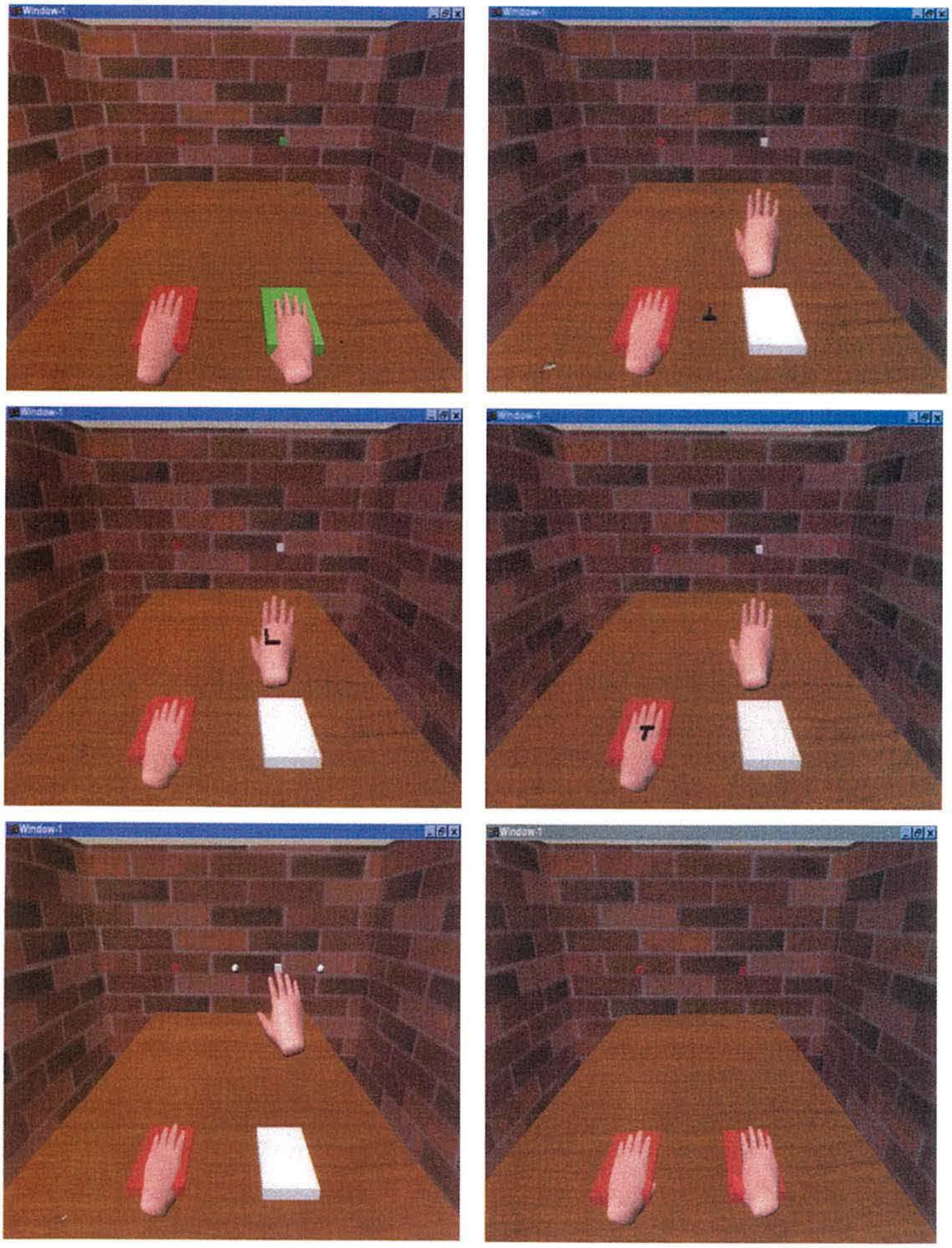

Figure 31

Screenshots of the Virtual Environment: Images by row from left to right illustrate the colour change of the hand rest and reach square prior to the appearance of the target, inverted letter T target located on the table, upright letter L target located on the active hand, upright letter T target located on the stationary hand, completed reach response with the appearance of the letter identification keys, and the return to start position on the hand rests.

This experiment consisted of two blocks of 216 trials in a within-subject 2 x 3 factorial design. The independent variables in this study were the Hand (Left or Right) and Target Location (Responding Hand, Non-Responding Hand, or Table). Hand and Target Location variables were presented randomly within each block. The dependent variable in this study was accuracy (measured as the percentage of responses activating the correct letter identification key).

Results

Accuracy (%) data obtained in this experiment was subjected to descriptive (mean) and inferential (ANOVA) statistical analysis. Mean duration of exposure to the target for all conditions was 42ms. Mean accuracy across all conditions for all participants measured 66%.

The primary focus of this experiment was to determine any differences in accuracy in response to targets located on versus off the virtual limb (Target Location). Descriptive analysis indicated that responses to a target located on the responding hand (M = 66%) and responses to a target located on the non-responding hand (M = 67%) were more accurate than responses to a target located off the hands on the table (M = 64%). Inferential analysis did not, however, reveal a significant main effect for Target Location ($F(1,23) = 0.79$, $p = .383$) and further analysis suggested that this difference in responses to targets located on and off the virtual limb might have been moderated by the responding hand. Analysis revealed a significant interaction between Hand and Target Location ($F(1,23) = 8.40$, $p = .001$). As illustrated in Figure 32, responses by the right hand were more accurate when the target appeared on the responding hand (M = 71%) and non-responding hand (M = 71%) as opposed to the table (M = 64%), whereas responses by the left hand were more accurate when the target appeared on the table (M = 64%) and non-responding hand (M = 64%) as opposed to the responding hand (M = 62%).

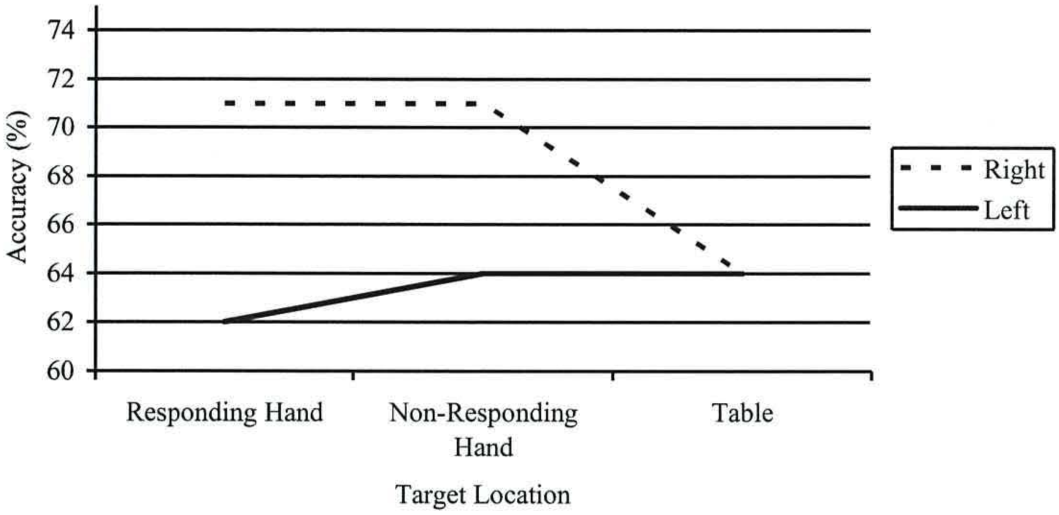

Figure 32

Mean Accuracy (%) as a function of Target Location and Hand in Experiment 17.

Additional analysis also revealed a significant main effect of Hand (*F*(1,23) = 19.17, *p* = .001): as expected, responses completed by the right hand (M = 68%) were significantly more accurate than responses completed by the left hand (M = 63%).

Although the descriptive analysis of this experiment found that responses to a target located on a virtual limb did appear to be more accurate than responses to a target located near a virtual limb, this difference was likely to be an effect of the responding hand. Responses by the right hand demonstrated enhanced accuracy for targets located on the hands rather than the table. This finding indicates an on/off effect and supports the hypothesis that responses to a target located on a limb will receive an attention bias. Responses by the left hand, however, demonstrated the same level of accuracy for the non-responding hand and the table and a lower level of accuracy for the responding hand. This finding does not indicate an on/off effect and, as a result, the overall results of this experiment cannot support the attention bias explanation.

Conclusion

Hari and Jousmaki (1996) found that responses to a target located on a hand were faster than responses to a target located near a hand and attributed these findings to a stimulus-response pairing. Evidence from Whiteley, Kennett, Taylor-Clarke, and Haggard (2004), however, suggested that this effect was more likely to be the result of an attention bias towards the body. Experiments completed in the previous chapters found that responses to a target located on a virtual hand are faster than responses to a target located near the virtual hand. Although the findings of Whitely et al (2004) provided compelling evidence to suggest that the on/off effect is the result of attention bias, results obtained in the previous chapters could not provide any empirical evidence to suggest that the effect observed in these experiments was due to an attention bias as opposed to a compatibility effect. Experiments described in this chapter aimed to differentiate between these two explanations in order to identify the basis for the observed on/off effect.

Compatibility effects require a direct relationship between a stimulus and a response (lifting same-sided hand in response to target), whereas an attention bias can be illustrated through an intermediate symbol (discriminating between two letter targets with a key press). Experiments 16 and 17 investigated the accuracy of responses to targets located on or near the virtual limbs. Participants were required to respond to the target by indicating the letter through a left or right hand lift (Experiment 16) or a left or right key touch (Experiment 17). Evidence indicating enhanced accuracy in response to targets located on the virtual hands could not be explained by a compatibility account thus any on/off effect identified in these experiments would support the attention bias explanation.

These experiments did not, however, reveal a significant preference for stimuli located on the virtual limb. Descriptive analysis suggested that there may be a slight bias towards stimuli associated with the hands, but this finding did not attain significance thus it cannot be taken as evidence in support of the attention bias explanation. It is important to note, however, that the lack of statistical significance observed in this study may have been the result of methodological flaws. Introspective reports by the participants highlighted the simplicity of the task demands in Experiment 16, thus any potential effect may have been masked by the fact that the accuracy levels for all conditions had reached a maximum. Furthermore, Experiment 17 involved the presentation of targets during the completion of a movement by the virtual limb and this may have interfered with the effect. Future research should attempt to resolve these issues by issuing a brief presentation of a letter target on or near a virtual limb after - rather than during - a movement of the hand. An additional confounding factor associated with both of these experiments is the perceptibility of the target. It is possible that the target located on table was easier to identify than the target located on the hand: the contrast between the colour of the rests/table and the target may have been more pronounced than the contract between the colour of the hands and the target. This factor could have resulted in enhanced accuracy in the off condition leading to the disruption of the on/off effect.

On the basis of the findings of the current experiments, it must be concluded that there is no evidence for an attention bias towards the body. Instead, it would appear that the on/off effects observed in the virtual reality experiments presented in this thesis are the result of stimulus-response compatibility. This finding is consistent with the conclusions of Hari and Jousmaki (1996) as they argued that the on/off effect was due to spatial stimulus-response compatibility between the target and the hand lift. However, this finding is inconsistent with the results of Whiteley et al (2004) as the on/off effect observed in their study was the result of an attention bias towards the body. It is interesting to note that the effect size observed in the Hari and Jousmaki (1996) experiment was 40ms whereas the average effect size in the current research was only 18ms. This difference in the effect size could indicate a crucial distinction between the real hands and the virtual hands. It is possible that attention is biased towards the real body, but is not biased towards the virtual body. In contrast, stimulus-response compatibility may influence the reactions in both the real and the virtual worlds. It could, therefore, be argued that the effect observed by Hari and Jousmaki (1996) in the real world was the result of both an attention bias and compatibility between the stimulus and the response. In the current experiments, however, the observed effect may have been the result of stimulus-response compatibility only. Indeed, this comparison could suggest that the stimulus-response compatibility explanation accounts for approximately half of the on/off effect (as illustrated in the current studies) and the attention bias explanation accounts for the remaining half of the on/off effect identified in the Hari and Jousmaki (1996) study.

Chapter 8

Research Implications for Personal Space and Body Schema

Research completed in this PhD aimed to investigate the flexibility of body space and schema by replicating the study conducted by Hari and Jousmaki (1996) in a simulated environment. Hari and Jousmaki (1996) found that motor activity is initiated more efficiently in response to stimuli located on the responding limb as opposed to off the responding limb. Experiments described in Chapters 3 to 7 adapted the Hari and Jousmaki (1996) method in order to further explore this on/off effect. Experiments 1 and 2 in Chapter 3 presented evidence to suggest that this preference for stimuli located on the body is flexible to the extent that it can be evoked in response to a virtual body. Experiments 3 to 15 in Chapters 4 to 6 explored the nature of this on/off effect in order to identify the optimal conditions for the preference for stimuli located on the virtual limbs. Experiments 16 and 17 in Chapter 7 aimed to identify the basis of this effect by comparing two competing explanations: attention bias towards the body and stimulus-response compatibility. The current chapter will discuss the findings of this thesis with regard to the concepts of personal space and the body schema.

Experimental Findings

Experiments 1 and 2 found that an on/off effect could be associated with virtual limbs. Experiments 3 to 6 revealed that responses to a target located on a virtual limb were faster than responses to a target located near the virtual limb, irrespective of the visual appearance, spatial orientation, and spatial location of the limb. Experiments 9, 11, and 12 revealed that the exact method of control over the virtual limb was flexible as this bias was recorded for a limb under the control of the opposite hands, feet, or tools. Experiments 7 and 8, however, found that the virtual limb did have to be under the predictable control of the individual and Experiment 10 found that this controllable virtual limb had to be intentionally manipulated to complete a specific task. In the absence of control over the virtual limb, Experiments 14 and 15 found some evidence to suggest that the illusory experience of tactile sensation from the virtual hand may result in a similar bias towards the limb. All of these experiments have identified the optimal conditions for the on/off effect in the virtual world: virtual limbs that appear to produce tactile sensation and/or are predictably controlled by the participant to complete a specific task will be subject to the on/off effect. Experiments 16 and 17 investigated the basis of this effect. These experiments did not find any evidence to support the attention bias explanation thus it was concluded that the on/off effect observed in this thesis was the result of compatibility between the stimulus and the response.

Analysis of the on/off effect has revealed some interesting comparisons between the findings of the previous and the current research. Hari and Jousmaki (1996) and Whiteley et al (2004) found that responses to targets located on the real hand were significantly faster than responses to targets located near the hand. The experiments in the current thesis revealed that this effect could be evoked in response to virtual limbs, although the effect size in this research was smaller than the effect size observed in the previous research. The effect size identified by Hari and Jousmaki (1996) was 20-40ms and the effect size identified by Whiteley et al (2004) was 33ms, whereas the average effect size in the current experiments was only 15ms. These differences may illustrate the distinction between the real hands and the virtual hands. Whiteley et al (2004) attributed the on/off effect observed in their study to an attention bias towards the body, but experiments completed in Chapter 7 found that there was no evidence for an attention bias towards the virtual limbs and concluded that the observed effect was the result of compatibility between the stimulus and the response. It is possible that the attention bias explanation and the stimulus-response compatibility explanation each account for approximately half of the total effect size with the real hands. In contrast, the virtual hands are not subject to an attention bias thus the overall effect size is reduced by half. Future research should further explore these differences between the real hands and the virtual hands in order to determine whether there are any conditions under which attention can be biased towards a simulated body.

Between-experiment analysis of the on/off effects observed in this thesis revealed some interesting differences and similarities across the experiments (please refer to Appendix 1 Figure 33 for an illustration of the mean RT in each study and Appendix 2 Figure 34 for an illustration of the effect size in each study).

Experiments 3 (mirror hands), 4 (feet), and 5 (cones) each demonstrated a slightly smaller effect size than Experiment 2 (baseline). It is interesting to note that this reduced effect size coincided with slower reaction times. Statistical analysis found significant differences in overall reaction times across the experiments as responses in Experiments 3, 4, and 5 were approximately 84ms slower than responses in Experiment 2. It is possible that the unusual presentation of the limbs in these experiments contributed to this difference and this theory was supported by the fact that the participants in Experiments 3, 4, and 5 expressed more discomfort with the task demands than the participants in Experiment 2. Statistical analysis, however, did not indicate a significant difference between the size of the on/off effects recorded in each experiment and descriptive analysis revealed that the variation in effect size accounted for only 6ms. It was, therefore, concluded that each of these experiments demonstrated a similar on/off effect.

In contrast to the above comparison, Experiment 6 (spatially displaced virtual limbs) demonstrated a considerably greater effect size than Experiment 2. This variation accounted for 31ms and, although this difference was not found to be statistically significant, this finding does suggest that there may be some minor discrepancies between these two experiments. Indeed, Experiment 6 was particularly unusual as it demonstrated the largest on/off effect across all of the experiments in the thesis. Analysis also revealed that overall responses in Experiment 6 were significantly slower than responses in Experiment 2. This finding could indicate a distinct difficulty in responding to distant targets and this theory could also explain the large on/off difference observed in this experiment. Downing and Pinker (1985) found that target detection was faster for stimuli located in near space rather than far space. On the basis of the premise that responses are faster for targets located on a limb and responses are faster for targets located in near space, it would be expected that the fastest responses would be recorded for targets located on a limb in near space (On condition in Experiment 2) and the slowest responses would be recorded for targets located off a limb in far space (Off condition in Experiment 6). This hypothesis is supported in the results of these experiments. An alternative explanation for the findings of this comparison is that targets located on the limb in far space are recoded as though they are located in near space because the virtual limb is regarded as a tool. Evidence suggests that targets located in far space can be recoded as though they are located in near space if they are within the reach of a tool (Ackroyd et al, 2002) and it is possible that the virtual limbs adopt the role of a tool in this experiment. This theory would suggest that responses to the target located on the limb in far space (On condition in Experiment 6) should be similar to the responses to the target located on the limb in near space (On condition in Experiment 2). The findings of this comparison, however, revealed that responses to targets on the far limb in Experiment 6 are considerably slower than responses to targets on the near limb in Experiment 2, thus it must be concluded that the targets located on the far limb are not processed in *exactly* the same way as the targets located on the near limb. However, although it is clear that the targets are not recoded to the extent that they are processed in the same way as a near hand, it is still possible that the targets on the displaced limb are recoded as though they are somewhat closer to the participant by virtue of their location on the hand tool and this theory could account for the large on/off difference observed in this study. The current findings, however, can not provide any conclusive evidence to explain why virtual limbs located some distance away from the body should be subject to a greater on/off effect, although some of the above discussion could form the basis for future research in this area.

Experiments 7 (immobile limbs) and 8 (unpredictable limbs) each failed to find an on/off effect thus the between-experiment analysis revealed a significant difference between Experiment 2 and Experiments 7 and 8. Analysis of the overall reaction times, however, failed to reveal any significant differences between these experiments. This finding highlights the similarities between each of these designs and emphasises the role of control in the on/off effect observed in Experiment 2. Further between-experiment analysis compared Experiments 2 and 7 with Experiments 14 (visuo-tactile feedback) and 15 (visual feedback). All of these studies adopted a similar visual presentation during the trials and the primary differences between the experiments were that Experiment 2 granted the participant control over the limbs, Experiment 14 provided the participant with concurrent visual and tactile feedback from the limbs prior to the trials, and Experiment 15 provided the participant with visual feedback prior to the trials. Analysis revealed a significant on/off effect in Experiments 2 and 14 and this finding suggests that both control and concurrent visuo-tactile feedback were important for establishing the bias towards stimuli located on the virtual limbs. These results indicated a larger effect size for Experiment 2 suggesting that control is the predominant factor in establishing the on/off effect but, in the absence of control, apparent sensation from the limbs can reinstate the effect. It would be interesting for future research to observe the effect size in controllable limbs following visuo-tactile feedback.

Experiments 9 (cross control virtual limbs) and 10 (cross control physical limbs) each identified a significant on/off effect, although the direction of the effect was different for each study. Experiment 9 found that responses to targets located on the limbs were faster than off the limbs whereas Experiment 10 found that responses to targets located off the limbs were faster than on the limbs. Analysis revealed that the effect observed in Experiment 9 was not significantly different to the effect observed in Experiment 2, although the effect size was found to be slightly larger for Experiment 9. This finding suggests that responses to targets located on the virtual limbs are faster than responses to targets located off the virtual limbs, irrespective of whether the limbs are under the control of spatially congruent or spatially incongruent physical hands. Experiment 10, however, observed a significant on/off effect in the opposite direction to the effects reported in Experiments 2 and 9, and this difference between targets located on and off the limbs was found to be the second largest in the thesis. This finding highlights the importance of goal driven intentions in the bias for stimuli located on the virtual limbs: virtual limbs in this experiment were irrelevant to the task thus they were inhibited to the extent that responses to stimuli associated with the limb were considerably slower. Analysis of the overall reaction times revealed that the responses were significantly faster in Experiment 2 than in Experiments 9 and 10, with Experiment 10 demonstrating the slowest reaction times. In Experiment 9, this finding is likely to be the result of the additional processing required to respond to the target with the contralateral physical hand. In Experiment 10, this finding is possibly due to the additional effort required to disregard the movement of the contralateral virtual hand in order to respond to the target with the ipsilateral physical hand.

Experiments 11 (Feet Control) and 12 (Tool Control) each demonstrate a significant on/off effect indicating a preference for stimuli located on a limb under the control of an alternative body part and a tool. Analysis reveals that this effect is similar to the effect observed in Experiment 2: the on/off effect reported in Experiment 2 is slightly larger than the effect reported in Experiment 12 and slightly smaller than the effect reported in Experiment 11, although the effect size variation across these studies measured only 5ms. However, overall reaction times in Experiments 11 and 12 were found to be significantly slower than in Experiment 2. In Experiment 11, this finding is possibly due to the fact that responses by the feet take longer to execute than responses by the hands. Hoffman (1991) found that the execution time for a movement by a hand was significantly faster than the time for an equivalent movement by a foot. In Experiment 12, this finding is likely to be due to the additional processing required to plan motor actions involving a tool and the additional weight of the tool during the lifting response.

Between-experiment analysis of the other effects observed in this research did not reveal any common main effects or interactions relating to the finger location and the target location across the different experiments (please refer to Appendix 4 Table 2 for the main effects and interactions recorded in each study and Appendix 5 Table 3 for the means recorded in each study). Analysis did, however, reveal a common preference for responses on the right side of fixation. Experiments 1 to 8 and 12 to 15 found that responses to targets located on the right side of fixation were faster than responses to targets located on the left side of fixation, and this finding was statistically significant in nine of these experiments. All of the participants in this research were right handed thus this result is likely to indicate their preference for right hand responses. This theory is supported by the descriptive data of Experiments 9 and 10. These studies found a preference for responses by the right physical hand: faster reaction times were recorded if the target side resulted in a response by the right physical hand, irrespective of the concurrent movement of the virtual hand. Experiment 9 recorded faster responses to left sided targets because they required a right physical hand response, whereas Experiment 10 recorded faster responses to right sided targets because they required a right physical hand response. These findings were not, however, found to be statistically significant. It is also interesting to note that Experiment 11 found that responses by the virtual feet demonstrated an unexpected preference for the left side, although responses by the virtual hands demonstrated a preference for the right side as expected. This finding suggests that the bias for side may be moderated to some extent by the appearance of the virtual limbs, since the virtual feet and the virtual hands were both under the control of the real feet.

Body Space and Schema

As noted in Chapters 1 and 2, research suggests that personal space and the body schema are malleable entities capable of projecting to incorporate an external object. Although the findings of the experiments described in the previous chapters are far from conclusive, results of these studies could be taken as further evidence for the flexibility of personal space and the body schema. Hari and Jousmaki (1996) found that responses to targets located on the body are faster than responses to targets located near the body, thus it can be suggested that responses are biased towards stimuli associated with the body schema and located within the realm of personal space. Experiments described in Chapter 3 found that responses to targets located on the virtual limbs are faster than responses to targets located near the virtual limbs. It may, therefore, be argued that the virtual limb has been incorporated into the body schema or that personal space has been projected to incorporate the virtual limb to the extent that responses are now biased towards the virtual body. In this context, 'incorporation' is operationally defined as the projection of personal space to space beyond the physical body or the alteration of the body schema to include objects not a part of the physical body.

Concepts of incorporation in relation to the body schema or personal space are often invoked as an explanation for responses to stimuli associated with objects linked to the body. Past research has often assumed that a similarity between responses to stimuli associated with the body and responses to stimuli associated with another object implies the incorporation of the new object into personal space or the body schema. Tool research has identified similar neural and behavioural responses to stimuli associated with both hands and tools (Berti & Frassinetti, 2000; Farne & Ladavas, 2000; Iriki, Tanaka, & Iwamura, 1996; Maravita, Spence, Kennett, & Driver, 2002; etc). This research has concluded that the similarity in the responses to the real limb and the external object (tool) suggests that personal space has been projected to incorporate the object or that the object has been incorporated into the body schema. Similar conclusions can be drawn for the findings in the current thesis. Hari and Jousmaki (1996) observed a bias for stimuli located on a physical hand and results of the experiments in this thesis revealed a similar (albeit smaller) bias for stimuli located on a virtual hand. It can, therefore, be concluded that this similarity in bias for stimuli located on the physical and virtual hand suggests that the virtual hand has been incorporated into the body schema.

Although these conclusions may seem logical and appropriate with regard to the notion of incorporation, findings from some of the later experiments (in particular, Chapters 5 and 6) suggest that the explanation for the observed phenomenon may be more complicated than a simple projection of personal space or inclusion of a new object into the body schema. Indeed, findings of the present research suggest that it may be necessary to review the current definitions of personal space and the body schema as they may present an inappropriate perspective of the representation of the body in the brain.

Conventional theories relating to space and schema have proposed that the mind holds a relatively fixed internal representation of the body and the space occupied by the body. These definitions have been criticised for proposing an inexplicable homunculus in place of an explanation for the wide variety of behaviours under exploration. Holmes and Spence (2006) argue that it may be prudent to avoid a single concept of body representation altogether, and propose that research should instead investigate numerous concepts of representation relevant to each specific aspect of bodily experience. Experiments presented in the current thesis suggest it may be appropriate to define one concept for the internal representation of the body in terms of what is under the control of the brain (control schema). Perhaps personal space and the body schema do not exist as an understanding of the body per se, but rather the mind holds a dynamic framework of the space and/or objects under the control of the individual; most commonly the physical body as this is the object most often under control, but also flexible enough to incorporate any other items controlled by the brain. This definition of the body schema is conceptually closer to the definition proposed by Gallagher and Meltzoff (1996). They suggested that the body schema is quite specifically responsible for information relating to the motor capabilities of the body and this proposal does appear to be supported by the findings of the research presented in the current thesis.

Most people have control of their own body so it could be proposed that the physical body will form the basic control schema, and this schema can then be projected to include any other object that is controlled by the individual for the purpose of completing a task. The findings of experiments completed in Chapters 3 to 5 are consistent with this theory since they reveal that the bias for stimuli located on with the virtual limbs will only be observed when the virtual limbs are controlled to complete a task. It may also be suggested that the schema could be retracted to exclude certain parts of the body if the individual is unable to exercise control over that area; although it may be hypothesised that it would simpler and faster to extend the schema to include external objects than to retract to exclude certain body parts, since it is more common for people to wield control over a tool than for people to lose control over parts of the body. Future research should explore the on/off effect in the real world for paralysed limbs in order to determine whether these uncontrollable limbs have been excluded from the schema. It is further proposed that there may also be a bias toward stimuli associated with an object not under the control of the individual, provided that the individual has experienced prior tactile feedback from the object. Since it is often the case that tactile feedback is usually only experienced from an object that is under control (such as the physical body), one might postulate that sensory feedback from an object (even illusory sensory feedback, as in the case of the rubber hand studies) will lead to the assumption that the object is likely to be under control, irrespective of actual evidence of command over the object. The findings of the experiments completed in Chapter 6 are consistent with this theory since they reveal a bias toward stimuli associated with a virtual limb not under the control of the individual, provided that the individual has experienced prior sensory feedback appearing to emanate from the limb. However, further research is required in this area in order to determine whether any other sensory experiences are capable of reinstating the on/off effect in response to non-controllable virtual limbs.

Future Research

Future research completed on the basis of the findings of the current thesis could further explore the preference for stimuli located on the body and investigate how this bias may influence behaviour in the real world.

One area of interest for future research is the attributed causes of the on/off effect. Experiments completed in Chapter 7 failed to find any evidence for an attention bias thus it was concluded that the on/off effect observed in the virtual world was the result of compatibility between the stimulus and the response. This conclusion was not entirely satisfactory, however, as there were a number of design flaws noted in Experiments 16 (high accuracy scores may have indicated a ceiling effect) and 17 (possible confounding effects due to the hand movements and possible perceptual difficulties in terms of lack of contrast between the target and the background). It would be prudent to further investigate the possibility of an attention bias explanation for the on/off effect in the virtual world by altering the current design to control for these factors. Future studies could adapt the design of Whiteley et al (2004) for the virtual environment in order to be able to compare the real hands and the virtual hands with some degree of confidence. If it were then found that the participant did not exhibit an attention bias towards the virtual limbs, future research could adapt this design further to explore the nature of this distinction between the virtual hands and the real hands. Experimental studies could focus on establishing the neural correlates of the on/off effect for real and virtual limbs or aim to determine the specific features absent in the virtual hands that are responsible for the attention bias towards the real hands. For example, it is possible that the attention bias is dependent on the limbs experiencing tactile feedback *and* being under the control of the participant (ownership and agency), thus one experiment could investigate whether attention will be biased towards controllable virtual limbs following illusory tactile feedback.

Further research in the virtual world could investigate the basis of the large on/off effect observed for the spatially displaced virtual limbs. This unusually large effect size may be the result of a bias against distant targets and a recoding of the far targets located on the limb as though they are in near space, but this theory requires more experimental investigation in order to draw any positive conclusions. It may also be interesting to explore the relationship between spatial displacement and the on/off effect by systematically measuring the effect size for targets located on and off limbs at various distances from the participant. These studies may provide additional evidence to identify the boundaries of peripersonal and extrapersonal space.

Future research should also focus on the on/off effect beyond the virtual world. Hari and Jousmaki (1996) revealed an on/off effect for real hands, Whiteley et al (2004) revealed an on/off effect for video images of real hands, and the current research revealed an on/off effect for virtual objects under the control of the individual. It is important to determine whether a similar bias can be observed for real objects under the control of the individual as these findings would be extremely relevant to the prosthetic limb industry and the tool and equipment industry. Furthermore, the identification of an on/off effect for external objects in the real world could lead to a further understanding about the flexibility of personal space and the body schema. Indeed, research could then begin to explore the outer limits of these concepts by investigating the possibility of an on/off effect for extremely large objects under our physical control (such as wheelchairs or vehicles) and distant objects under our verbal control (such as other people responding to our orders). It is not suggested that the body schema or personal space can be projected to incorporate such objects, but rather that these studies may provide further evidence to support the concept of the control schema proposed above and explore the potential for this particular type of representation.

Real World Applications

Research completed in Chapters 3 to 7 revealed that responses to a target located on a virtual limb under the control of the participant were faster than responses to a target located near the virtual limb. This result implies that a tool wielded by an individual to complete a task may receive similar processing to the body itself and these findings have clear implications for understanding the complexities of the human-object interface.

These experiments have highlighted the features of the virtual object that are essential for a bias towards stimuli located on the object. In particular, these experiments have revealed that the physical appearance, spatial orientation, and spatial location of the virtual object are irrelevant. In contrast, it is essential that the individual has reliable control over the virtual object to complete a task, although the exact nature of control is open to some degree of flexibility allowing a bias to exist even in cases of control through an alternative body part and secondary control through the use of a tool. It may be suggested that successful control over any object can make an individual feel as though the object has become a part of their own body (consider the closeness that exists between a tennis player and his racket) and will thus enhance the ability of the individual to use the object for its given purpose. All of this information is extremely pertinent to the manufacturers of artificial limbs, tools, sports equipment, vehicles, control panels, etc. In particular, manufacturers of artificial limbs require their patients to quickly adjust to the replacement limb in order to improve physical and psychological recovery following an amputation. Findings outlined above would suggest that it is not necessary for an artificial limb to closely resemble the patients' own limb (although this may be important for social acceptance and self-confidence issues), whereas it is necessary for the artificial limb to be under the control of the patient. Training for amputee patients should, therefore, emphasise control by encouraging the patient to complete specific tasks with the artificial limb (for example, pushing a button, lifting an object, taking a step, etc) in order to successfully incorporate the new addition.

Chapter 9

Research Implications for Virtual Reality

Immersive virtual reality is a relatively new technology currently in the earliest stages of research and development. Initial exploration of virtual reality inspired extravagant claims and, like many novel and unusual technological advances, virtual reality was believed to be the future for telecommunication, entertainment, education, and a host of other genres. Popular press presented a futuristic view of society dominated by fully interactive virtual simulations designed to eradicate the inconvenience of having to actually travel to the place or person one wishes to visit (Biocca & Levy, 1995).

Virtual reality has not quite lived up to these expectations (although it may be argued that the current use of the internet and video conferencing, rather than realistic simulations, has begun to create a society of this nature) and, as a result, has often been dismissed in most areas as an impractical or inappropriate technology. Current psychological research is, however, beginning to appreciate the potential for simulated environments in a range of settings and, although the practical and theoretical limitations are acknowledged, further advances are now beginning to present virtual reality as a viable option for medicine, education, and, perhaps most importantly in the context of the current thesis, psychological research.

Experimental Findings

Research exploring the use of tools has found that the body schema and personal space can be modified to incorporate an external object, and the current experiments suggest that the body may be represented in a flexible 'control schema' capable of projecting to virtual objects under the control of the individual. These findings have significant implications for the use of virtual reality in industry, education, and research. In particular, these findings suggest that an individual will respond to stimuli in the virtual world in the same way as they respond to stimuli in the real world, provided that they are able to control their virtual body. More importantly, these virtual interactions are not restricted by practical constraints, and this freedom could allow individuals to fully interact in a virtual world regardless of distance or location.

Some examples of the potential applications of these findings include social or business meetings taking place in an online room using simulated bodies, doctors in one country performing operations in another through the use of a virtual body mapped to a robotic arm, patients suffering delusions regarding their body shape being trained to accept their actual form through the use of a simulated body, etc (please see the later sections of this chapter for more details on these applications). The findings of the current research suggest that the virtual body used in all of these examples could be accepted as a part of the self to the extent that one would feel as though they were acting within the simulation, rather than simply interacting with a computer system. It is certainly true that the subjective account of any individual engrossed in a computer game will report that the individual feels as though they are 'inside the game'.

The subjective experience of the individual in the virtual world is identified as a paradox by Sanchez-Vives and Slater (2005): the participant in a virtual world is cognitively aware that the environment is fake, yet they respond as though it were real - for example, an individual may know that the virtual precipice is an illusion yet they may still experience a fear of falling. This paradox can be applied to the findings of the current experiments: participants are aware that the virtual limbs are not their own hands, yet they exhibit a similar bias for stimuli located on their simulated limbs as they do for stimuli located on their real limbs. Sanchez-Vives and Slater (2005) explored the virtual experience through the concept of 'presence'. Presence is defined as feeling and behaving as though one were inside the simulation, and this can be measured through self-reports in questionnaires and behavioural measures such as whether the participant will sway while observing a moving visual field or duck in response to a low flying virtual object. The on/off effect observed in this thesis could act as another behavioural measure of presence. In this case, presence is specifically related to the virtual body and participants in this research were found to exhibit presence by behaving as though the virtual body was their own body. As noted by Sanchez-Vives and Slater (2005), it is clear that more research is required in this area in order to further explore the subjective feelings of the individual in the virtual world, in addition to investigating the reactions of the participant to virtual stimuli.

Research completed in the previous chapters suggests that certain conditions must be met in order for the virtual body to be processed in a similar way to the real body.

Chapters 3 to 6 explored the nature of the on/off effect to identify those features necessary for the incorporation of a virtual object into the schema. Both control and, to a lesser extent, visuo-tactile feedback were highlighted as potentially critical and it was concluded that the virtual world should provide the individual with reliable and predictable control over their virtual body and the experience of tactile feedback from their virtual body. Chapter 7 explored the basis of the on/off effect by comparing an attention bias explanation with a stimulus-response compatibility explanation. The research conducted in Chapter 7 could not support the theory that attention was biased towards the virtual body thus it was concluded that the on/off effect was the result of stimulus-response compatibility. This finding suggests that the optimal relationship between the simulated body and the virtual environment will ensure that the required responses are compatible with the stimuli. Subramanian, Gutwin, Sanchez, Power, and Liu (2005) emphasise the importance of stimulus-response compatibility in their guidelines for successful use of virtual reality systems. It is clear that the simulation must follow this guideline in order to take advantage of the on/off effect.

To summarise, the on/off effect associated with the virtual body could be taken as evidence for presence within the simulation and indicate that the virtual limbs have been incorporated into the control schema. The on/off effect is dependent on the individual exercising predictable control over the virtual limbs and/or experiencing tactile feedback from the virtual limbs. The basis of the on/off effect in the virtual world is compatibility between the stimulus and the response, and it is therefore essential that the activities within the virtual environment maintain compatible stimulus-response mapping.

Limitations of Virtual Reality

It is acknowledged that there are currently several significant limitations on the practical application of this technology: high quality systems can be exceptionally expensive; affordable systems often fail to display a realistic simulation; and designing a simulated environment to a high standard of realism requires a significant amount of time and expertise. Sanchez-Vives and Slater (2005) note that the physical world is exceptionally complicated thus it would be extremely difficult to render all of the intricate detail in a simulation, even with the most advanced virtual reality equipment. Research completed in the previous chapters utilized inexpensive virtual reality equipment and the simulations did not appear entirely realistic as some aspects - particularly the virtual limbs - had a slight cartoon appearance. The illustration of the virtual hand did not include a depiction of fingernails, knuckle joints, hair, or minor skin imperfections such as colour fluctuations, moles, beauty spots, freckles, or wrinkles. It is also worth noting that even lifelike virtual hands would appear unrealistic to the participant because they would not look like the actual hands of each unique individual: virtual limbs were entirely uniform thus did not allow for gender, race, or individual differences. However, although the virtual limbs in this research did not meet a high standard of realism, the findings of the experiments suggest that the visual appearance of the virtual limbs is irrelevant to the on/off effect. In particular, Experiment 5 found that responses to targets located on a virtual cone were faster than responses to targets located off the virtual cone. These findings led to the conclusion that the participant will demonstrate a preference for the virtual limbs, irrespective of the appearance of the limb. This proposal is supported by Sanchez-Vives and Slater (2005) who found that the visual realism of the virtual environment is not important for the individual to experience presence within the simulation. It was noted in the previous chapter, however, that the effect size observed for the virtual hands in the current experiment was considerably smaller than the effect size observed for the real hands in the study by Hari and Jousmaki (1996). Furthermore, the effect size observed for hand-shaped virtual limbs in Experiment 2 was greater than the effect size observed for cone-shaped virtual limbs in Experiment 5. It is possible that the visual appearance of the virtual limbs could account for these differences: perhaps the participant will exhibit a preference for stimuli located on any object under their control, but this preference is strongest if the visual appearance of the object is consistent with the appearance of their real body. It would be interesting for future research to explore whether a larger effect size would be observed for more realistic virtual limbs.

Another issue relating to realism in the virtual environment is the controllability of the virtual hands, and this issue is considerably more important than the visual appearance of the limbs in the context of the current findings. Real hands are entirely controlled by the participant to the extent that each individual finger can be moved. In contrast, the virtual hands in this research were inflexible and, although each hand could be moved as a whole, the individual fingers could not be manipulated independently.

This lack of complete control over every aspect of the virtual limb could also account for the difference in effect size observed between the virtual hands in this thesis and the real hands in the study by Hari and Jousmaki (1996). Future research could explore the importance of control by using complete sensor gloves, rather than a single finger sensor, to allow full control over all aspects of the virtual hands.

An additional criticism of the simulation employed in the previous experiments is that the virtual object did not always accurately match the real objects for size - for instance, the virtual hands were approximately 10% smaller than the physical hands - due to the available space on the display screen. Actual sized objects would have dominated the restricted perception of the world through the small screen so it was necessary to ensure that objects were small enough to allow a complete view of the simulation. It is important to note, however, that the participants did not appear to notice that the virtual hands were smaller than their own hands: indeed, both participants and experimenters experienced surprise at the realisation that the virtual hands were not life sized when the screen was switched to allow a concurrent view of the real and simulated worlds.

Future technological advances may eventually provide psychology with a virtual simulation that is indistinguishable from the real world. There may, however, be an inherent limitation associated with the use of virtual reality irrespective of the degree of realism in the design of the simulation. Virtual reality is not actual reality. Participants will always be aware of the crucial difference between the virtual body and the physical body. Virtual reality may provide a high quality procedure for preliminary investigation of psychological phenomenon; however, virtual reality does not offer an ecologically valid alternative to real world research so experiments should always be replicated beyond the simulation before the findings can result in a satisfactory conclusion.

Further limitations associated with virtual reality are that the equipment can be cumbersome and bulky making it difficult to transport and uncomfortable to wear. Stewart (1992) suggested that a participant wearing a full set of virtual reality equipment resembled a 'mime in scuba gear'. Research completed in the previous chapters utilized only a headset and finger sensors (as opposed to a full body suit), yet even this limited amount of equipment was uncomfortable for the participant, particularly due to the restrictions imposed by the lengths of cable. Also, many of the participants in the previous experiments complained that the headset caused strain on the neck or fitted too tightly around the head and most participants felt that the equipment was not suitable for an experiment lasting approximately one hour. An additional problem associated with the equipment utilised in this experiment was that the awkward fitting of the headset meant that the display screen did not rest directly in front of the eyes for all of the participants: some participants were forced to tilt their heads forwards or backwards throughout the duration of the experiment in order to obtain a clear view of the simulation.

Ethical issues must also be considered with regards to the use of virtual reality systems in psychological research. Some of the potential problems relating to physical discomfort have already been described above, and additional research by Regan and Price (1994) has highlighted other complaints commonly associated with prolonged exposure to virtual simulations. They found that 61% of participants reported symptoms similar to motion sickness during twenty minute periods in an immersive virtual reality system. Typical symptoms reported included dizziness, nausea, headaches, and eyestrain to such an extent that 5% of the participants decided to withdraw from the study. It is, however, important to note that several other studies utilising immersive virtual reality have reported no ill effects (including Riva, 1998) and further research has noted that these negative reactions can be overcome through gradual and repeated exposure to the simulation (Regan, 1995). None of the students participating in the studies described in this thesis reported any of the symptoms of motion sickness either during or after the experiment, although many of the participants did feel uncomfortable towards the end of the hour due to the awkward headset and continual need to focus on virtual stimuli.

Despite these various methodological difficulties, immersive virtual reality did appear to be appropriate for the current research. Although the reduced on/off effect size relative to the real hand research could be explained by some of the limitations of the virtual reality equipment (such as visual realism or controllability of limbs), the results of these experiments still demonstrate a significant preference for stimuli located on the virtual limbs. Furthermore, although some of the participants reported minor discomfort and many would have preferred the experiment to run for a shorter duration, none of the participants reported severe difficulty or felt the need to withdraw from the study at any time. These findings suggest that the equipment and the simulation were sufficient for the needs of this experimental paradigm. These findings also suggest that the minor problems associated with the simulation and equipment do not impact on the potential for virtual reality to be used in a variety of settings. Furthermore, recent technological advances are beginning to address many of the limitations described previously and current virtual reality systems do appear to be suitable for medical, training, and research purposes.

Applications of Virtual Reality in a Clinical Setting

Applications for virtual reality technology have been widely recognised in the clinical sector. Rose (1996) noted that virtual reality techniques could be adopted to improve assessment, enhance rehabilitation of impairments, reduce disabilities, and minimise the negative effects of handicaps. Virtual reality could aid diagnosis of impairments by measuring patient performance in a safe environment; for example, virtual simulations could measure the extent of visual disturbances in patients with disorders such as ataxia and strabism (Kuhlen & Dohle, 1995). Virtual reality could enhance the rehabilitation of disorders by acting as a training aid to assist the recovery of function; for example, virtual training scenarios could teach patients with motor disturbances (such as pareses, apraxia, and paralysis) to perform a range of movements from basic to complex using their remaining motor functions (Kuhlen & Dohle, 1995). Virtual reality could lessen the negative effects of certain handicaps by acting as an effective support aid; for example, virtual reality could assist patients with speech deficits by translating hand gestures into spoken words (Kuhlen & Dohle, 1995).

Virtual reality can also be employed in surgical procedures in order to expand the availability of surgical expertise and reduce the need for time-consuming travel by surgeons. Marescaux, Leroy, Gagner, Rubino, Mutter, Vix, Butner, and Smith (2001) argue that recent technological advancements (including improved bandwidth and time delays in electronic signals) have allowed the development of robot-assisted telesurgery. They report a successful laparoscopic remote robotic cholecystectomy on a 68-year-old female: robotic arms at the remote site in Strasbourg removed the gallbladder and the operating surgeon was able to manipulate these arms from the control site in New York. As noted by Marescaux et al (2001), telesurgery across vast distances will ensure that patients throughout the world are able to access the same level of surgical expertise and this globalisation of medical treatment will lead to an improvement in patient welfare.

Virtual reality systems have also been applied in the treatment of psychological disorders. Specific phobias have been particularly susceptible to the effects to exposure therapy in a virtual environment (Garcia-Palacios, Hoffman, Carlin, Furness, & Botella, 2002). Virtual environments allow the therapist to create a fear inducing experience in a safe situation and examples of the effective use of this method have been recorded for the treatment of acrophobic patients (Rothbaum, Hodges, Kooper, Opdyke, Williford, & North, 1995), agoraphobic patients (North, North, & Coble, 1996), patients with social phobias (Anderson, Rothbaum, & Hodges, 2003), and patients with a fear of flying (Rothbaum, Hodges, Watson, Kessler, & Opdyke, 1996).

Virtual reality methods have been particularly effective for interventions associated with the body schema and body image. Research described in this thesis has focused on the concept of the body schema and this mental representation of the body tends to derive from a sensory perspective: conclusions drawn in this thesis suggest that the body schema is simply a representation of what is under the control of the individual. Body image, on the other hand, is defined as an emotional representation of the body based on how the body appears to the individual (Schilder, 1935/1950). Gallagher and Meltzoff (1996) noted that the body schema and body image are usually believed to interact; for example, changes in the body schema (improved body through exercise) often lead to changes in body image (enhanced satisfaction with body). There are, however, some cases of dissociation between body schema and image indicated by a failure to appreciate the body as it actually exists. This dissociation is particularly notable in patients suffering eating disorders as their body schema may indicate a normal or even underweight figure, yet their body image indicates distinct dissatisfaction with a body perceived to be overweight. Research has adopted the use of virtual reality for the treatment of patients diagnosed with anorexia nervosa or bulimia nervosa: one such treatment that has attained some success recently is the Experiential Cognitive Therapy known as Virtual Environment for Body Image Modification devised by the Virtual Reality Environment in Psychoneuro-physiological Assessment and Rehabilitation 2 research project (Riva, 1998). This treatment has been designed to enhance awareness of the body schema and improve levels of satisfaction associated with body image and current findings suggest that it has a significant impact on understanding and acceptance of the physical body (Riva, 1998; Riva, Bacchetta, Baruffi, Molinari, 2002; among others).

Virtual reality methods have also been proposed as a more effective alternative to the mirror box technique in the treatment of phantom limb pain. Ramachandran (1993a, 1993b) argued that the pain experienced in a phantom arm is partially due to the feeling that the limb is frozen in a particularly uncomfortable position or occasionally spasms into a clenched position with the fingernails cutting into the palm. Mirror boxes produce a visual illusion of movement in the phantom by allowing the patient to observe movement of the existing limb in the same location as the phantom limb. Ramachandran (1993b) found that these mirror boxes could give the patient an opportunity to move the phantom limb into a more comfortable position or unclench the phantom hand and this experience was successful in alleviating pain in numerous amputee patients. Murray, Pettifer, Caillarte, Patchick, and Howard (2005), Murray, Patchick, Caillette, Howard, and Pettifer (2006), and Murray, Patchick, Pettifer, Caillette, and Howard (2006) adopted a similar method using virtual limbs instead of mirror reflections. Patients were presented with a controllable virtual limb in the same spatial location as the phantom limb in order to allow the experience of movement. Evidence to date has revealed that this technique can be highly effective in reducing phantom limb pain and, although further research is needed in order to develop appropriate clinical interventions, early indications suggest that this may be an effective rehabilitation technique for assisting patients to adjust to the loss of a limb and existence of a phantom.

Findings of the research completed in the previous chapters suggest that stimuli associated with a virtual body will receive similar processing to stimuli associated with an actual body. These findings support the use of virtual reality techniques in treatments of physical and mental disorders and imply that future research should aim to expand on the possible application of virtual reality technology in the clinical sector.

Applications of Virtual Reality in Education and Training

Applications for virtual reality technology have also been acknowledged in the educational sector. Virtual reality systems are currently being developed to provide realistic 3d anatomical models for medical training and teaching, structural models for engineering and architectural training, flight simulations for pilot and astronaut training, and driving simulations for advanced driver training (Rose, Attree, Brooks, Parslow, Penn, & Ambihaipahan, 2000). Indeed, Stevens, Hernandez, Johnsen, Dickerson, Raij, Harrison, DiPietro, Allen, Ferdig, Foti, Jackson, Shin, Cendan, Watson, Duerson, Lok, Cohen, Wagner, and Lind (2006) found that virtual reality training systems can even be utilised to teach medical students how to engage in appropriate doctor-patient interactions.

Virtual simulations have also been adopted in safety training for children and social skills training for people with autistic or learning disorders (Strickland, 1997; Parsons & Mitchell, 2002). Parsons, Leonard, and Mitchell (2006) highlight the effectiveness of these methods in a report outlining the personal reflections of two young people with autistic spectrum disorders following social skills training in a simulated environment. Both of the adolescents agreed that the training was an enjoyable experience and identified specific examples of how the training had or could assist them in their everyday lives.

Findings of the research completed in the previous chapters support the application of virtual reality techniques in education and training. Virtual reality methods are especially appropriate for training in high risk occupations when there is an inevitable conflict between the effectiveness of training in a real life setting and the risks associated with on-the-job training (for example, surgeons learning to perform complex operations, pilots learning to operate aircraft control panels, etc). This conflict can be resolved through the use of a simulated environment as a training aid because it will allow the student to practise activities in a safe, yet realistic, environment. These methods would be particularly effective if combined with physical feedback from a haptic stimulation device since tactile information is highly relevant in many occupational activities. In particular, surgeons rely heavily on both visual and haptic feedback during medical procedures: for example, Marescaux et al (2001) utilised video screens to display the patient and haptic stimulation devices to control the robotic arms in their successful robot-assisted telesurgery. Future research should focus on designing training techniques incorporating both visual and haptic simulations.

Applications of Virtual Reality in Industry

Applications for virtual reality have been recognised in many areas of industry. Fernandes, Raja, and Eyre (2003) propose the use of a virtual reality system known as the 'Cybersphere' for training purposes in the manufacturing sector, demonstration purposes in civil engineering and sales (such as estate or travel agents), and entertainment purposes in the games industry. All of these industrial sectors would benefit from the use of a fully interactive simulated environment designed to display a realistic representation of an activity, design, or product.

Research completed in the previous chapters found that participants were able to successfully integrate a pair of virtual hands into their body schema. This finding would suggest that virtual limbs could be applied as an interface between real limbs and mechanical arms in the work place. Many areas of manufacturing require mechanical arms to complete tasks that would be impossible for a living being (handling certain chemicals, working in a hostile or sterile environment, etc). Virtual reality techniques may improve control over the mechanical arms as the human controller could complete the task with virtual hands in a realistic simulated environment and these limbs could then be mapped to the movement of mechanical arms in the real world. Furthermore, virtual reality techniques would allow the actions of the individual in the simulated environment to be mapped to robotic activity anywhere in the world. For example, specialist engineers based in the UK could perform complex procedures in a simulated virtual environment to be transmitted to robotic arms for completion of the project in the US. As noted in the training applications, these methods would be particularly effective if combined with physical feedback from a haptic stimulation device since tactile information is highly relevant in many occupational activities (for example, surgeons rely heavily on touch during operations) and future research should focus on designing techniques incorporating both visual and haptic simulations.

Applications of Virtual Reality in Research

Research completed in this thesis found that responses to stimuli located on the virtual limb are faster than responses to stimuli located near the virtual limb, and this preference has been compared with the preference for stimuli located on the real limb to conclude that the responses to the virtual body are similar to the real body. These findings suggest that research could explore the representation of the real body in space by investigating responses to a virtual body in a simulation. It is acknowledged in the current thesis, however, that the virtual body is not processed in exactly the same way as the real body. Evidence revealed crucial differences between the real and simulated worlds: the virtual on/off effect is considerably smaller than the real on/off effect, and this finding could be due to the fact that there does not appear to be an attention bias towards the virtual limbs though there is evidence for an attention bias towards the real limbs. Exploration of body representation through the use of virtual reality will be fundamentally limited since there is a clear distinction between the attention bias towards the real limbs and the lack of bias towards the virtual limbs. However, despite these limitations, research in this area can still investigate the on/off effect observed in the current thesis by ensuring that the required responses are compatible with the simulated stimuli. Furthermore, future exploration of the differences in attention bias between the real and virtual limbs could provide us with a unique insight into the features that allow the individual to distinguish between their own body and other objects under their control (for example, virtual limbs).

Virtual reality is a particularly efficient method for the investigation of personal space and the body schema because an experiment completed in a simulated environment can fully manipulate the area around and within the realm of the body. Experimental designs using a real hand, rubber hand, hand shadow, or plastic rake are restricted by the physical constraints of the object under investigation. Experimental designs using a pair of virtual limbs do not suffer these physical constraints. Virtual limbs of any visual appearance can be situated in any spatial location within the simulation; indeed, virtual limbs can suddenly change appearance or location during the course of the experiment. Virtual limbs can be presented complete with associated sensory feedback by instructing the participant to interact with a physical object in conjunction with the virtual object; or, alternatively, virtual limbs can be presented with inappropriate or devoid of sensory feedback in order to investigate the role of sensation. Virtual limbs can respond to normal control of a corresponding limb, crossed control of an opposite limb, activity of an alternative body part, or even verbal commands. Virtual limbs can even provide a fully operational body part to a disabled person allowing the investigation of adaptations in personal space and the body schema following the loss of function in a particular part of the body.

Virtual reality is an ideal medium for research in general as it acts to bridge the gap between ecological validity and experimental control. Research conducted in the laboratory is often criticised for lacking ecological validity whereas field research will often fail to implement the rigorous controls necessary for stringent scientific study. Virtual reality can provide the experimenter with absolute control over a simulated environment: stimuli can be presented in a reasonably realistic setting, targets can appear or disappear suddenly in any location, impossible situations or objects can be created, and responses performed by the participant can be recorded precisely. Experiments conducted in a virtual world remain entirely under the direction of the experimenter and are thus restricted only by the inventiveness of the researcher.

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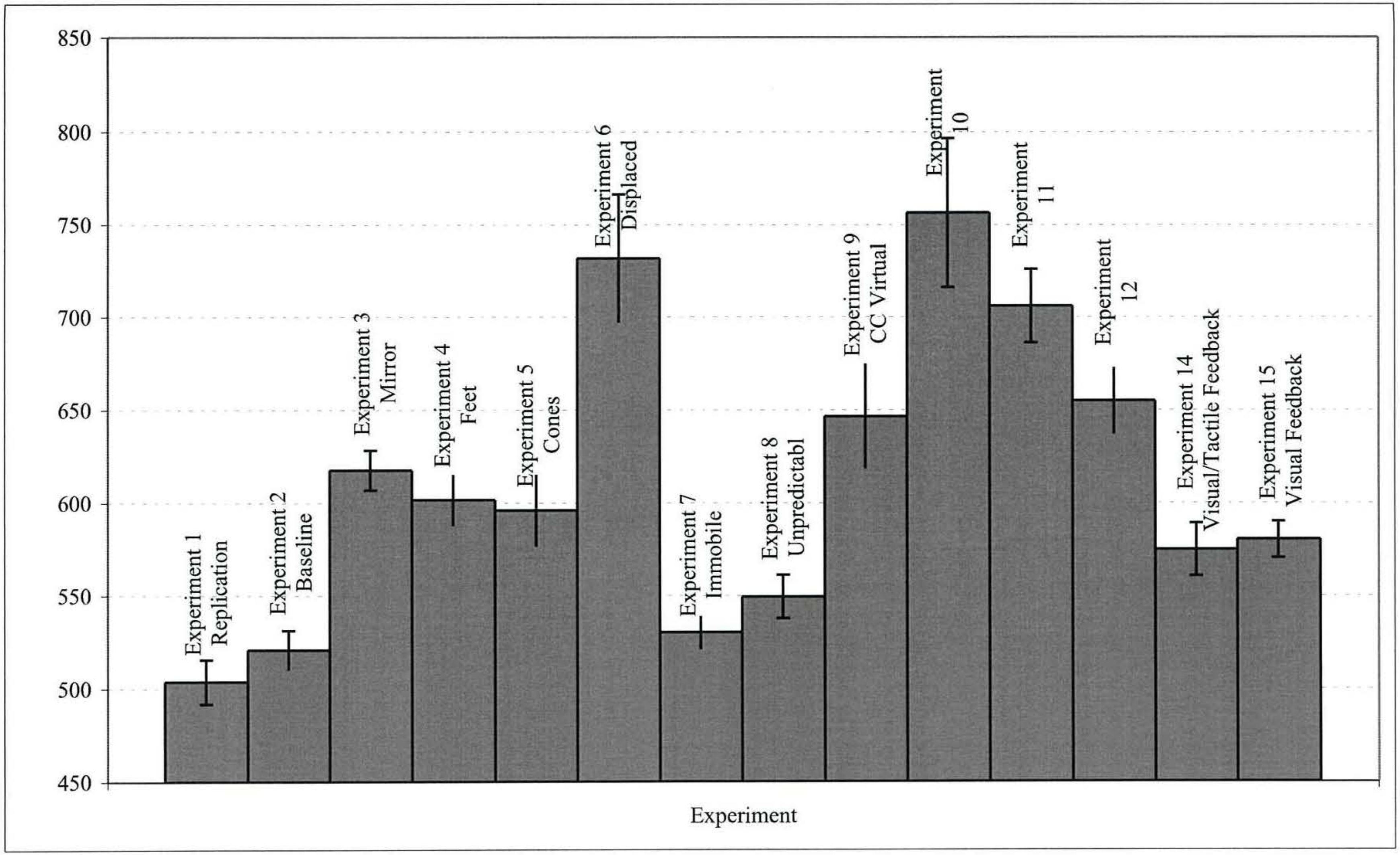

Figure 33

Mean Reaction Times (ms) for Experiments 1 – 12 and 14 – 15 (error bars represent mean standard error)

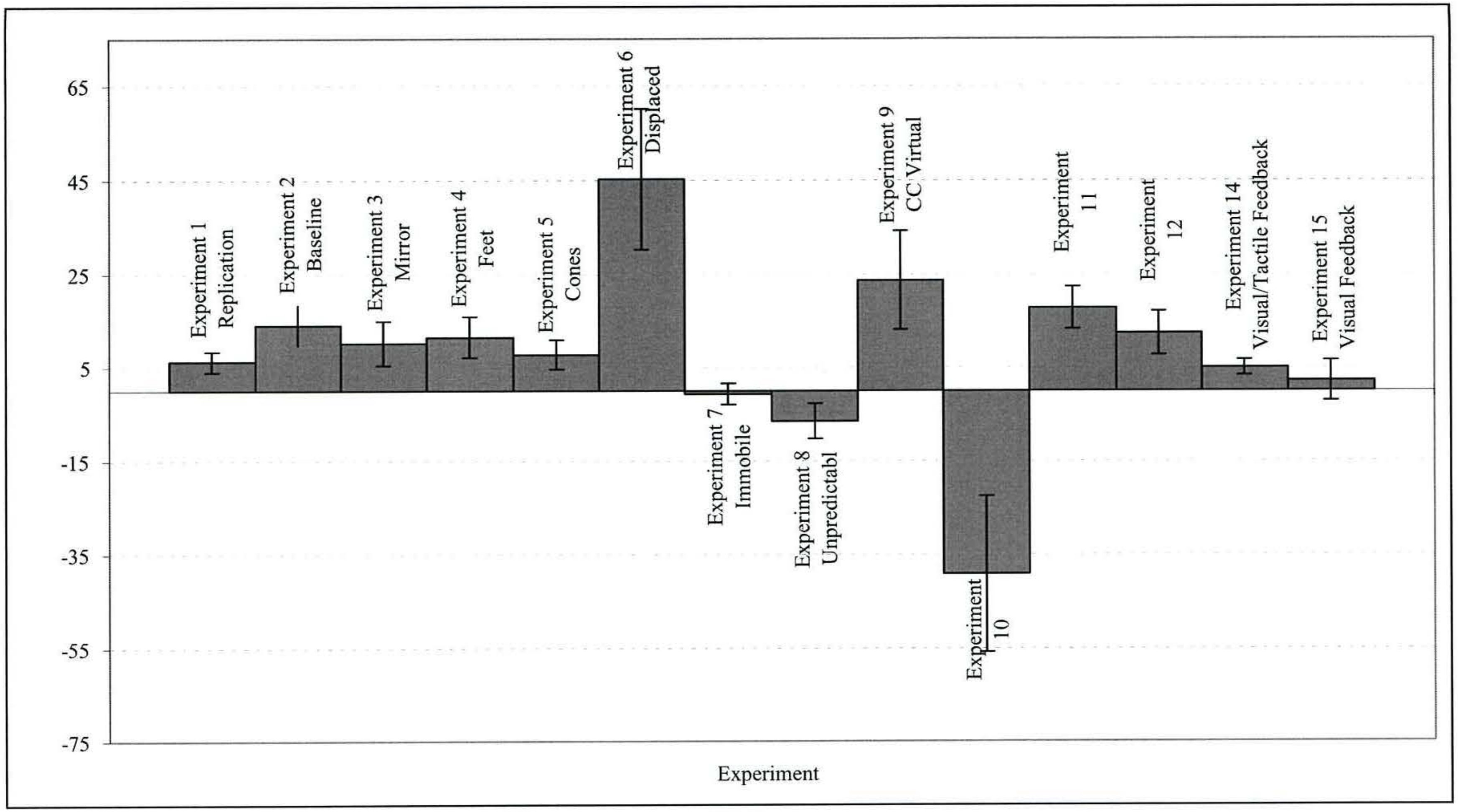

Figure 34

Mean difference in Reaction Times (ms) between responses to a target located off the hand/foot/cone and responses to a target located on the hand/foot/cone (off minus on) for Experiments 1 – 12 and 14 – 15 (error bars represent mean standard error)

Table 1

Analysis of RT (ms) On/Off Effect for Experiments 1 – 12 and 14 – 15

	On/Off Effect			Comparison with Baseline (Experiment 2)
	Main Effect	Mean (SE) On	Mean (SE) Off	Interaction
Experiment 1: Hari and Jousmaki (1996) Replication	F=8.55 p=.008	501 (11.81)	507 (12.10)	N/A
Experiment 2: Baseline Experiment	F=10.60 p=.003	514 (10.21)	528 (11.01)	N/A
Experiment 3: Appearance: Mirror	F=4.59 p=.043	613 (10.56)	623 (11.49)	F=0.36 p=.055
Experiment 4: Appearance: Feet	F=6.87 p=.015	596 (13.03)	607 (14.58)	F=0.17 p=.682
Experiment 5: Appearance: Cones	F=6.17 p=.021	592 (19.03)	600 (20.01)	F=1.39 p=.244
Experiment 6: Spatial Proximity	F=9.06 p=.006	709 (28.56)	754 (40.97)	F=3.97 p=.05
Experiment 7: Immobile Virtual Hands	F=0.1 p=.761	530 (8.97)	530 (8.91)	F=9.14 p=.004
Experiment 8: Unpredictable Response	F=2.88 p=.103	553 (9.15)	546 (8.01)	F=12.83 p=.001
Experiment 9: Crossed Control Virtual Response	F=5.04 p=.035	635 (25.49)	658 (31.55)	F=0.71 p=.4
Experiment 10: Crossed Control Physical Response	F=5.54 p=.027	776 (46.25)	737 (35.21)	F=9.60 p=.003
Experiment 11: Virtual Limbs as Hands or Feet controlled by Hands or Feet	F=15.31 p=.001	697 (14.39)	715 (16.89)	F=0.37 p=.545
Experiment 12: Virtual Limbs with Tools controlled by Tools	F=6.96 p=.015	649 (17.06)	661 (18.98)	F=0.07 p=.79
Experiment 14: Visual/Tactile Feedback from Immobile Virtual Limbs	F=8.91 p=.001	572 (14.01)	577 (14.50)	F=3.83 p=.056
Experiment 15: Visual Feedback from Immobile Virtual Limbs	F=0.26 p=.618	579 (9.37)	581 (10.71)	F=3.82 p=.056

Table 2

Analysis of RT Main Effects and Interactions for RT in Experiments 1 – 12 and 14 – 15

	Main Effects			Interactions			
	Target Side	Target Location	Limb Location	Target Side x Target Location	Target Side x Limb Location	Target Location x Limb Location	Target Side x Target Location x Limb Location
Experiment 1: Hari & Jousmaki (1996) Replication	F=121.72 p=.001	F=8.55 p=.008	N/A	F=2.22 P=.150	N/A	N/A	N/A
Experiment 2 : Baseline Experiment	F=186.30 p=.001	F=2.97 p=.10	F=10.15 P=.004	F=4.85 P=.038	F=5.062 p=.034	F=9.59 p=.005	F=0.75 p=.396
Experiment 3: Appearance: Mirror	F=2.84 p=.105	F=0.90 p=.35	F=1.73 P=.20	F=4.05 P=.056	F=1.61 p=.22	F=5.06 p=.034	F=9.11 p=.006
Experiment 4: Appearance: Feet	F=34.79 p=.001	F=25.31 p=.001	F=3.03 P=.10	F=0.60 P=.447	F=0.321 p=.58	F=6.57 p=.017	F=1.13 p=.299
Experiment 5: Appearance: Cones	F=46.65 p=.001	F=0.49 p=.49	F=1.82 P=.19	F=4.43 p=.05	F=2.56 p=.123	F=6.05 p=.022	F=0.04 p=.84
Experiment 6: Spatial Proximity	F=8.26 p=.009	F=0.79 p=.38	F=2.39 P=.14	F=0.99 P=.330	F=1.97 p=.174	F=8.73 p=.007	F=0.15 p=.701
Experiment 7: Immobile Virtual Hands	F=85.99 p=.001	F=18.42 p=.001	F=0.15 P=.70	F=5.78 P=.025	F=2.36 p=.138	F=0.05 p=.823	F=13.09 p=.001
Experiment 8: Unpredictable Response	F=5.93 p=.023	F=17.78 p=.001	F=0.36 P=.56	F=0.34 P=.565	F=1.19 p=.286	F=2.80 p=.108	F=0.36 p=.555
Experiment 9: Crossed Control Virtual Response	F=0.14 p=.71	F=1.54 p=.23	F=1.34 P=.26	F=1.76 p=.20	F=0.26 p=.62	F=5.40 p=.029	F=3.45 p=.076
Experiment 10: Crossed Control Physical Response	F=1.33 p=.260	F=0.22 p=.645	F=3.05 P=.094	F=0.41 P=.526	F=964 p=.336	F=5.75 p=.025	F=1.09 p=.308
Experiment 11: Virtual Limbs as Hands or Feet controlled by Hands or Feet	F=5.77 p=.025	F=10.64 p=.003	F=3.71 P=.066	F=10.08 P=.004	F=0.08 p=.776	F=13.26 p=.001	F=0.00 p=.993
Experiment 12: Virtual Limbs with Tools controlled by Tools	F=65.79 p=.001	F=17.59 p=.001	F=2.51 P=.127	F=5.25 P=.031	F=2.58 p=.122	F=6.89 p=.015	F=6.79 p=.016
Experiment 14: Visual/Tactile Feedback from Immobile Virtual Limbs	F=29.27 p=.001	F= 4.02 p=.057	F= 3.26 P=.084	F= 3.07 P=.093	F= 8.7 p=.007	F=8.70 p=.007	F= 0.32 p=.577
Experiment 15: Visual Feedback from Immobile Virtual Limbs	F=3.36 p=.08	F=0.82 p=.375	F=0.04 P=.846	F=13.02 P=.001	F=0.02 p=.905	F=0.31 p=.585	F=9.13 p=.006

Table 3

Summary of RT Mean (ms) and Standard Error (in parenthesis) in Experiments 1 – 12 and 14 - 15

	Target Side		Target Location		Limb Location	
	Left	Right	Inner	Outer	Inner	Outer
Experiment 1: Hari & Jousmaki (1996) Replication	528 (8.75)	480 (8.35)	*Upper* 507 (9.40)	*Lower* 501 (9.09)	N/A	N/A
Experiment 2 : Baseline Experiment	553 (7.17)	490 (5.95)	518 (7.6)	524 (7.06)	504 (5.88)	539 (8.12)
Experiment 3: Appearance: Mirror	625 (6.06)	609 (7.29)	619 (6.84)	616 (6.67)	624 (6.83)	612 (6.63)
Experiment 4: Appearance: Feet	622 (8.46)	582 (8.20)	614 (8.78)	589 (8.19)	592 (8.27)	612 (8.77)
Experiment 5: Appearance: Cones	626 (11.71)	569 (9.60)	595 (11.84)	600 (10.30)	589 (9.97)	606 (12.06)
Experiment 6: Spatial Proximity	759 (21.39)	703 (18.97)	725 (23.66)	737 (16.53)	710 (13.65)	753 (25.26)
Experiment 7: Immobile Virtual Hands	553 (5.08)	508 (5.02)	525 (5.32)	535 (5.73)	529 (5.67)	532 (5.43)
Experiment 8: Unpredictable Response	560 (4.39)	539 (6.78)	540 (5.11)	559 (6.26)	548 (5.53)	551 (5.97)
Experiment 9: Crossed Control Virtual Response	641 (24.40)	652 (9.33)	641 (14.89)	652 (21.46)	661 (23.92)	632 (10.33)
Experiment 10: Crossed Control Physical Response	775 (27.38)	735 (22.93)	761 (26.61)	750 (235)	728 (21.38)	782 (28.48)
Experiment 11: Virtual Limbs as Hands or Feet controlled by Hands or Feet	692 (8.95)	721 (10.40)	700 (9.01)	714 (10.42)	694 (10.48)	719 (8.89)
Experiment 12: Virtual Limbs with Tools controlled by Tools	681 (9.34)	629 (10.78)	641 (9.11)	669 (11.40)	664 (11.22)	646 (9.48)
Experiment 14: Visual/Tactile Feedback from Immobile Virtual Limbs	587 (7.71)	562 (7.05)	572 (7.30)	577 (7.70)	569 (7.05)	580 (7.90)
Experiment 15: Visual Feedback from Immobile Virtual Limbs	585 (5.70)	575 (6.09)	578 (5.31)	582 (6.46)	579 (5.59)	581 (6.23)

Table 4

Complete list of RT Means (ms) and Standard Error (in parenthesis) for every condition in Experiments 1 – 12 and 14 - 15

	Target Left				Target Right			
	Target Inner		Target Outer		Target Inner		Target Outer	
	Limb Inner	Limb Outer	Limb Inner	Limb Outer	Limb Inner	Limb Outer	Limb Inner	Limb Outer
Experiment 1: Hari & Jousmaki (1996) Replication	*Target Upper* 533 (12.72)		*Target Lower* 524 (12.24)		*Target Upper* 482 (11.96)		*Target Lower* 478 (11.90)	
Experiment 2 : Baseline Experiment	525 (10.56)	582 (16.02)	537 (11.75)	570 (15.68)	463 (9.07)	507 (13.63)	490 (9.69)	502 (13.19)
Experiment 3: Appearance: Mirror	616 (9.99)	631 (12.52)	638 (13.46)	616 (12.36)	623 (17.17)	605 (14.31)	616 (13.40)	594 (13.36)
Experiment 4: Appearance: Feet	621 (13.56)	644 (18.15)	607 (20.67)	617 (14.53)	576 (15.93)	617 (20.12)	562 (13.04)	571 (14.37)
Experiment 5: Appearance: Cones	612 (20.87)	645 (30.39)	616 (20.60)	632 (21.25)	553 (18.06)	571 (20.32)	574 (18.36)	577 (20.84)
Experiment 6: Spatial Proximity	710.12 (25.89)	808 (68.99)	750 (25.31)	768 (35.71)	654 (22.79)	729 (52.68)	725 (32.12)	705 (38.27)
Experiment 7: Immobile Virtual Hands	549 (10.92)	550 (8.62)	549 (11.31)	563 (9.95)	499 (8.81)	503 (9.86)	517 (11.33)	511 (10.28)
Experiment 8: Unpredictable Response	547 (7.21)	555 (8.53)	561 (9.20)	576 (9.71)	535 (13.86)	521 (9.70)	549 (12.74)	552 (16.93)
Experiment 9: Crossed Control Virtual Response	630 (49.53)	628 (21.14)	693 (78.19)	613 (25.71)	657 (20.56)	648 (17.76)	662 (19.50)	640 (17.52)
Experiment 10: Crossed Control Physical Response	785 (68.13)	791 (60.46)	731 (31.32)	795 (54.64)	723 (31.56)	743 (47.60)	674 (25.79)	801 (66.34)
Experiment 11: Virtual Limbs as Hands or Feet controlled by Hands or Feet	673 (18.17)	713 (17.36)	689 (20.08)	694 (15.87)	685 (16.58)	728 (19.35)	731 (27.14)	741 (18.18)
Experiment 12: Virtual Limbs with Tools controlled by Tools	670 (15.65)	671 (18.83)	695 (20.28)	688 (20.25)	617 (19.50)	605 (15.39)	674 (30.00)	622 (16.97)
Experiment 14: Visual/Tactile Feedback from Immobile Virtual Limbs	577 (13.71)	590 (16.46)	588 (16.35)	594 (15.75)	552 (12.91)	570 (14.89)	560 (12.79)	565 (16.20)
Experiment 15: Visual Feedback from Immobile Virtual Limbs	581 (8.20)	579 (11.63)	587 (13.56)	594 (12.04)	572 (9.02)	582 (13.38)	578 (13.36)	570 (12.99)