The Ties that Bind: An Investigation into the Effect of Action Restriction on Motor Simulations

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Abstract

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Rachel Shaw

This thesis examines the relationship between physical capabilities and the mental simulation of actions. Behavioural research suggests that the ability to understand of an action is directly related to the ability to perform it, an idea consistent with the Embodied theory of Cognition. The present work aims to further explore the relationship between the body and cognition and investigate whether the restriction of an action or movement disrupts the simulation of movements during motor imagery tasks, which have been shown to elicit motor activations upon performance.

This theory was investigated in a series of seven motor simulation experiments during which participants' movements were restrained. Studies 1-3 investigated simulations that occur unconsciously through the observation of manipulatable objects. Studies 4-6 investigated simulations that occur during performance of mental transformations of manipulatable objects and body part stimuli. The results of these studies found no significant difference in performance when movement was restricted compared to when free to move. Study 7 investigated simulations that occur consciously through the observation of actions performed by another individual and found a significant effect of restriction on performance. The findings of these studies indicate that the ability to perform a movement is required for the accurate simulation of actions when an action is being observed but not when a simulated action is required on a stationary object, which suggests a variable relationship between the body and cognitive processes.

This thesis offers an interesting contribution to the Embodied Cognition debate and provides a further insight into the relationship between the motor and visual systems.

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Chapter 1- Introduction

The nature of human cognition has been of great interest to psychologists for many years and has led to the development of a number of theories regarding its function in the day to day running of the human body. Traditional theories of cognition proposed that it is abstracted from the body and works independently to the sensory and motor systems as an information processor, primarily involved in the inputting, storage and outputting of information (Wilson, 2002). More recent theories of cognition, however, suggest that the body plays a pivotal role in the way we think and behave, with sensory and motor experiences influencing cognitive processes in a way previously disregarded by the traditional cognitivists (Barsalou, 2003). This theory of cognition is known as Embodied Cognition.

One of the central concepts of the Embodied theory of Cognition is that knowledge and understanding is gained through the simulation of events in our minds, using previous sensory-motor encounters of the situation as a basis by which to determine how to behave (Barsalou, 2003). As we encounter new situations, we collate the sensory and motor activations associated with these experiences in order to draw from them when the situation arises again. An implication of this theory is that if knowledge is obtained through bodily experiences, it is constrained not only by the experiences and situations that we have encountered but also by the physical capabilities of the individual. Consequentially, this would suggest that our knowledge, and therefore our cognitions, can in turn be both enhanced and restricted by our motor systems.

The relationship between our body and cognitive development had garnered increasing popularity over the last decade, with many cognitivists rejecting the more traditional theories of cognition for Embodied Cognition to the extent that mental simulation is now considered a rudimentary cognitive process (Barsalou, 2003). A wealth of research has been conducted into the relationship between our body and the ability to perform such simulations and has led to the conclusion that the current positioning of our body directly affects performance in cognitive tasks involving motor imagery, such as the mental rotation of body parts (Parsons, 1988). When performing these tasks, we use the current positioning of our body as a starting point at which to begin the transformations, therefore our cognitions are very much influenced and dependent on our physical state. Much of the research in this area has focused on the position of the body during these tasks (Parsons, 1988), however few have considered the effect our physical capabilities have on performance in motor-based cognitive tasks and those that do are unable to form firm conclusions about the exact role our bodies play in these circumstances. The aim of this chapter is to review the area of Embodied Cognition, with a focus on visual perception and motor action, as well as the mechanical processes employed such as simulation and imagery, to explore whether manipulating our physical capabilities on a temporary basis can interfere with our performance in motor-related tasks and if so, what implications this may have on our understanding of cognition.

1. Embodied Cognition

The theory of Embodied Cognition first came to prominence as a result of work by the ecological psychologist Gibson (1979) on his theory of Affordances. Gibson (1979) proposed that all objects within ones environment communicate “affordances” to the individual. These affordances refer to suggestions of potential interactions that can be performed with these objects, determined and constrained by the sensory-motor abilities of the observer and the environment in which they are viewed. Gibson (1979) believed that the affordances an object offers are an intrinsic part of the object and are not created as a result of the needs of the observer. However, he suggested that whilst all affordances are available to be perceived at all times, the affordances available to the individual at a particular moment are shaped and constrained both by what they desire and what they are capable of doing at that moment in time. Gibson’s (1979) theory was one of the first to suggest that the body played an active role in the shaping of our cognitions and focused on the proposition that the affordances an object communicates to us are determined and constrained by our physical capabilities. For example, a chair may afford climbing to an adult but the physical limitations of a new-born infant will mean it won’t afford climbing to them.   Similarly, although a chair will afford climbing if one is trying to get somewhere, it will afford sitting if one is tired. This idea forms the basic underpinning of the theory of Embodied Cognition- what we perceive, and in turn cognition in general, is influenced by our bodily states.

Gibson’s (1979) theory proposed that objects communicate affordances for general use due to features such as location and orientation in relation to the individual, and according to restraints posited by the environment. For example, a cup with its handle to the left will afford a left handed grasp if a person is stood in front of it, as it is this action that is most appropriate for comfortable interaction, however if the individual is positioned to the left of the mug, it will afford a right handed grasp (DiSperati & Stucci, 1997) . Gibson (1979) focused on the general actions that are potentiated by the object, such as the most appropriate hand to use, but Ellis and Tucker (2000) suggested that objects can also communicate micro affordances to the viewer. These micro affordances communicate the exact details of motor actions needed to perform on the object, such as grasp size, wrist orientation and hand shape. As a result, seeing an object will not only elicit a simple grasping or reaching movement but a very specific motor action tailored to that individual object in its current form and location.

Gibson (1979) believed that the affordances an object communicates to the observer are dependent upon the physical capabilities of the perceiver and the environment in which the perceiver is in, but research suggests that they also depend on the goal state of the individual (Kaschak & Glenberg, 2000). Objects can have multiple affordances for many different actions but it is only the parts of the object that are relevant to the intended goal of the individual that will afford an action at any one time. Borghi (2003) uses the example of a car to illustrate this point- when driving a car, it is the steering wheel that affords the action as it is this part that is crucial to our goal of driving the vehicle, however if we were aiming to mend the car, the motor would be most salient and afford the actions. The number of actions that an object can afford is potentially limitless therefore in order to interact appropriately with an object, it is essential that we have a goal system in place so that we can perform with the object in a way that fits with our needs and goals.

1.1 Cognition and Action

The theory of Embodied Cognition had developed over the years from Gibson's (1978) theory of Affordances to a more sophisticated view which proposes that we can gain an understanding of the world around us and how to act within it through motor and sensory interactions with our environment (Allport, 1985). However, this change from an object focused theory to one that encompasses areas such as social interaction has led to a re-evaluation of the mechanics of cognition. Traditional theories viewed cognition as an independent information processor, with the perceptual and motor systems acting as input and output systems, feeding sensory information to higher level cognitive areas which systematically process the information and produce the appropriate response (Wilson, 2002). The Embodied Cognition theory, however, proposes that cognition has a more direct and encompassing relationship with the perceptual and motor systems. In line with this theory, Wilson (2002) proposed that the purpose of cognition is primarily for the mediation of action and had developed over the years in order to directly facilitate interactions within our environment, a claim supported by research into visual perception.

Vision- The existence of two visual systems

Heilman and Valenstein (2003) believed that high-level vision has two main goals- the identification of stimuli, and the determination of their location. Satisfaction of these processes is crucial if we are to be able to interact within the environment and therefore it is only when these goals have been realised that we can act upon objects in the world. Neuropsychological research has found that these goals are achieved separately by two relatively independent systems, located in the dorsal and ventral cortices (Goodale & Milner, 1992). Ungerleider and Mishkin (1982) first suggested the existence of two separate areas involved with visual processing, which originate from the primary visual area but project to two different cortex; the ventral stream, which is involved with the identification and recognition of an object and projects to the infero-temporal cortex, and the dorsal stream, which is concerned with spatial processing and projects to the posterior parietal cortex. These cortical systems are often referred to as the “what” and “where” systems due to the nature of their processing (Ungerleider & Mishkin, 1982).

Early evidence for the existence of two separate visual streams was found in primate brain lesion studies. Ungerleider and Mishkin (1982) found that damage to the infero-temporal cortex led to deficits in visual discrimination tasks but preservation of the monkey’s ability to localise objects, whereas lesions in the posterior parietal cortex resulted in deficits in object localisation but preserved visual discrimination ability. These findings support the “what” and “where” system discriminations, however Goodale and Milner (1992) proposed that the key difference between the dorsal and ventral streams is not the type of information they carry but the way this information is used. They suggest that the purpose of the ventral stream is not merely to identify the object but to mediate the conscious perception of objects by supplying abstract representations of the visual world to be stored for future reference. By working “off line”, the ventral stream enables individuals to recognise and interpret visual inputs and plan future actions, in turn creating an internal representation of the world which helps to establish a visual memory. These representations will be discussed later in this chapter. Goodale and Milner (2006) proposed that we access these visual memories in order to perform certain visuo-motor activities; as our initial efforts become more skilled and automatic, the contribution made by the ventral stream reduces and is replaced by streamlined actions involving the dorsal stream.

Ungerleider and Mishkin (1982), in their original research, proposed that the dorsal stream is chiefly concerned with the localisation of objects. Goodale and Milner (1998), however, suggested that the dorsal stream plays an equally important role in the mediation of actions, with its main function being the direction of behavioural interactions with objects in real time. Support for the action mediation theory of the dorsal stream can be found in monkey lesion studies, which found a significant impairment in both reaching ability towards an object and the forming of appropriate hand shapes during prehension of objects after lesion to the posterior parietal cortex (Ungerleider and Mishkin, 1982). Gallese, Fadiga, Fogassi, Luppino & Murata (1997) also found that temporary disablement of certain areas of the posterior parietal cortex in monkeys led to an impairment in appropriate hand shaping when reaching towards on object. Research into neurons in the dorsal stream of monkeys found isolated neuron activity according to the type of motor response made to stimuli (Ungerleider & Mishkin, 1982; Milner & Goodale, 1998). These neurons were sensitive not only to movements made by the arms and hands, however, but also to eye movements. Ungerleider and Mishkin (1982) found that some cells fired when the object was the target of a prehensile movement, such as a reach or a grasp, whereas others responded when the object was the target of eye movements, for example saccadic or tracking movements. This would suggest that although the localisation of objects does occur in the dorsal stream, this information is processed separately according to the type of movement being executed. It is worth noting, however, that single neuron research has come under scrutiny in recent years due to the difficulty in accurately interpreting the cause of the activation and therefore the results of these studies should be interpreted with caution (Uithol, van Rooij, Bekkering & Haselager, 2011). Overall, the collective findings of these studies provide support for the action mediation theory in that the dorsal stream is not only involved in the localisations of objects but uses this localisation in the development and guiding of actions towards those objects.

Neuropsychological research into humans has also found similar dissociations between perception and action control. Patients with lesions in the posterior parietal lobe often suffer from optic ataxia, a brain disorder characterised by impairment in the reaching ability of patients but preservation of the perception of objects. Coupled with an inability to reach accurately towards a target object, optic ataxia sufferers often have an inability to form the correct hand shapes and movements required for grasping the object (Jeannerod, 1986). In a study by Perenin and Vighetto (1988), patients with optic ataxia made significantly more errors than healthy participants when reaching their hands towards and through a large rotated slot. Similarly, optic ataxia patients showed a significant deficit in the scaling of hand apertures when reaching towards a target object (Jeannerod, 1986). When reaching towards an object with the intention of picking it up, healthy individuals will adjust their hand shape as they come closer to the object to bring it in line with the geometric properties of the item, usually starting with a hand shape that closely resembles that required to ensure only minimal adjustments (Jeannerod, 1984). Optic ataxia patients, however, will often begin their grasping movement with their fingers spread wide apart and will fail to adjust appropriately according to the size of the object, even though they are still able to process and report the positioning of the target object. This suggests that damage to the posterior parietal cortex prevents patients from being able to integrate the visual information of the object with their motor behaviour; therefore optic ataxia is in fact a visuo-motor disorder, rather than purely a motor disorder. Conversely, research has also shown a similar disorder resulting from damage to the ventral stream, known as Visual form agnosia. Visual form agnosia is characterised by an inability to visually identify objects or their perceptual properties such as orientation. A case study of the patient D.F, who suffered from visual form agnosia, showed a distinct inability to report the orientation of a rotated slot but when asked to post her hand through it, she was able to accurately orient her hand and insert it correctly, starting as soon as her hand left its starting position (Milner, Perrett, Johnston, Benson, Jordan, Heeley, Bettucci, Mortara, Mutani, Terazzi & Davidson, 1991). Similarly, when required to reach towards and pick up an object, her hand shape was correctly scaled for each item before actual contact took place, which is in line with healthy individual performance. However, when asked to make a manual judgement of the object size using her fingers and thumb, the size portrayed showed no relation to the actual size of the object. Again, these findings suggest that although motor prehension ability is preserved, patients with visual form agnosia are unable to integrate their motor systems with the visual information that is being processed. As these findings show, patient D.F is impaired in the same areas that patients with optic ataxia excel at and vice versa, suggesting a double dissociation between the functions of the ventral and dorsal streams, which in turn supports the assumption that the visual perception of objects and the mediation of reaching and grasping actions occurs in two relatively dependent streams that require mutual integration for accurate perceptions and actions to occur.

The emergence of Embodied Cognition, and the subsequent change in viewpoint of many Cognitivists, has, over the last decade, led to a re-evaluation of the visual cortex and its role in the perception of actions. Prior to the EC theory, the motor system was seen as the exclusive hub of all action planning and execution, with sensory input mediating the outgoing motor actions (Garbarini & Adenzato, 2004). However, research has found evidence to suggest that the visual system plays an important role in the priming of actions through visual perception. Neurophysiological research into the premotor cortex of primates has found the existence of two distinct types of visuomotor neurons: Canonical neurons and Mirror neurons (Murata, Fadiga, Fogassi, Gallese, Raos and Rizzolatti (1997); Gallese, Fadiga, Foggassi & Rizzolatti, (1996). These neurons respond during both action and object observation tasks; however their activations differ slightly and have different implications regarding the theory of Embodied Cognition.

Canonical Neurons and Motor resonance

Research into the relationship between vision and action has shown that when a three dimensional object is observed, the neurons that respond when a congruent response is performed are automatically activated, even when there is no intention to act. These visuomotor neurons are known as Canonical neurons and the dual activation that occurs is the motor resonance effect (Murata, et al 1997). The Theory of Event Coding (TEC; Hommel, Musseler, Aschersleben & Prinz, 2001) proposes that the motor resonance effect occurs as the result of an overlap in the neural systems involved in vision and action planning. Classic theories of information processing focus on perception and action planning as two separate entities, however the TEC proposes that perception and action planning are in fact much the same process, in so much that both are required for the completion of each other. Hommel et al (2001) suggest that the process of perception involves the active acquisition of information regarding our physical relationship to the environment in which we are in, such as where attention is focused, along with bodily positioning and movements, whereas action planning involves the processing of the perceptual information of the environment. The TEC proposes that perception and action planning share the same cognitive codes, or representations, in our mind, therefore performance of one task automatically results in the activation of the other task, hence the motor resonance effect.

Support for the motor resonance effect can be found in neuropsychological research. When a graspable object is visible, parietal and prefrontal regions have been found to respond independently of any intentions to act, resulting in the appropriate actions being activated (Riddoch, Edwards, Humphreys, West & Heafield, 1998). The parietal system is involved in the encoding of both action related and visuospatial information, including the location of the object and the direction of movement needed to interact with it (Anderson, 1987, as cited in Tucker & Ellis, 1998). Many of the cells in this system are also responsive to the relationship between the visual object and the micro-affordances, such as grasp size, required to act upon it (Taira, Mine, Georgopoulos, Murata & Sakata, 1990). This automatic activation of the appropriate response codes leads to an increased readiness to execute that action, thereby facilitating the performance of subsequent compatible actions (Ellis & Tucker, 2000). This compatibility effect is known as motor facilitation.

An example of motor facilitation can be found in the Stimulus-Response compatibility (SRC) effect, where responses are facilitated when aspects of the target stimulus match an aspect of the response, i.e. the hand used to respond to the object is the same one afforded by the object (Ellis & Tucker, 2000). In a classic study by Tucker and Ellis (2001), participants were presented with images of mugs with their handles turned either to the left or right. They found that even when the direction of the handle was not a critical part of the study, participants were faster at responding using the hand that was compatible with the handle location of the object compared to responses using the incompatible hand. Similarly, Tucker and Ellis (2001) found that objects that afforded a grasping action were responded to faster when a grasping, or power, action was made compared to a pinch, or precision, response even when the affordance was not critical to the study. The results of these studies demonstrate that viewing objects, even when there is no intention or possibility of interaction, automatically potentiates the appropriate response needed by activating the response codes required for this action, resulting in faster responses when the response codes and subsequent actions match. Fenske, Aminoff, Gronau and Bar (2006) propose a top down processing method of visual object recognition whereby an object or item is categorised due to the features it is made from, resulting in the early processing of the motor features of an object before recognition can occur. This suggests that the motor features are automatically processed upon perception of the object, resulting in the activation of the appropriate motor codes required to interact with it. This in turn posits that the perception of an object alone is sufficient to communicate the action required to interact with it, providing support not only for Gibson's (1978) theory of affordance but also for the TEC theory that action planning and perception are functionally inseparable.

The TEC states that that perception and motor planning share the same codes and representations; therefore participation in one of these activities leads to the automatic activation of the other, as demonstrated by the motor resonance effect (Hommel et al, 2001). Behavioural research has demonstrated that presentation of a visual object automatically activates action codes appropriate for that object, resulting in faster responses when congruent responses are made (Tucker & Ellis, 1998). However, Craighero, Fadiga, Rizzolatti and Umilta (1998, 1999) found that preparing to grasp an object produced enhanced processing of stimuli congruent with that object and action, suggesting a bi-directional relationship between perception and action. In their study, participants were required to prepare a grasping movement towards an oriented bar and execute the movement upon presentation of a visual stimulus that was either congruent or incongruent with the grasp being prepared. They found facilitated detection times when the grasp and stimulus were congruent. Craighero et al (1999) suggest that the preparation of a grasping movement increases motor readiness to perform that action and reduces the time it takes to detect, discriminate and process a visual object with the same intrinsic properties. Research suggests that response preparation creates a mental simulation of a grasp of the stimulus and activates the motor areas that control the execution of the response, therefore potentiating the motor responses preparation through a visuomotor priming effect. This in turn makes the visual system more responsive to objects that afford the action being primed, thereby facilitating detection of compatible objects. (Jeannerod, 2004; Tucker & Ellis, 1998; Symes, Tucker, Ellis, Vainio & Ottoboni, 2008).

Research has also found that the priming of actions at a more general level can facilitate the detection of compatible objects. In a study by Fagioli, Hommel and Schubotz (2007) participants performed a reaching or grasping action towards a physical stimulus before performing a visual discrimination task in which they had to find a deviant stimulus amongst predictable stimuli. When the nonconforming stimulus had been detected, participants had to perform their prepared reaching or grasping response. The results found that when the deviant stimulus differed to the other stimuli according to size, detection of the deviant stimuli was significantly faster when a grasping response has been previously prepared. When the stimulus differed in location, however, detection was significantly faster when reaching responses were performed compared to grasping responses. Fagioli et al (2007) proposed that as grasping actions are related to the size of an object, the preparation of a grasp response led to a priming effect for size related objects. Similarly, reaching actions are dependent upon the location of an object and therefore preparation of a visually directed reaching response facilitates detection of location based stimuli. These findings suggest that the priming of a very general action, such as reaching or grasping, increases our sensitivity to aspects of objects that are congruent with those actions by activating the appropriate response codes required for interaction, thereby facilitating detection of compatible objects. Therefore, if primed about the physical information of an object before seeing it, responses towards that object should be facilitated (Craighero et al, 1999). Likewise, if the appropriate action is primed and prepared before presentation of the object, detection of congruent objects and execution of that response should be faster. The idea of general action priming is in contrast to the work on micro affordances conducted by Tucker and Ellis (1998) who suggests a very specific motor activation response upon observation of objects and preparation of actions. However, Matheson, White and McMullen (2014) found specific action potentiation effects towards both manipulatable objects and non manipulatable animals, which suggest a more general stimulus-response compatibility effect of potentiation guided by the directing of attention towards specific object features. These findings provide support for the TEC, which proposes that perception and action planning share the same action codes therefore facilitating each other's performance, and also demonstrate the bi-directional relationship between our perceptual and motor systems.

Mirror Neurons

The motor resonance effect as described in the previous section is a key notion of the Embodied cognition theory, however research has found that the neural systems involved in the execution of actions are also automatically activated when observing others performing a motor action (Gallese, et al, 1996). Investigations into this finding has led to the discovery of so called "mirror neurons" in the brain that automatically fire when watching someone else perform an action that the viewer themselves is capable of. The term "mirror neurons" comes from the understanding that these neurons reflect the actions of others onto their own neural networks, effectively "mirroring" the behaviours of others. Gallese et al (1996) first discovered a set of neurons in the ventral premotor cortex of a macaque monkey that automatically fired when the monkey observed another performing an action within its own repertoire. These neurons typically responded to one action only, which led to the conclusion that different actions are coded separately in the brain. For example, Gallese et al (1996) found specific neuron sets that responded when a grasping action occurred, whereas others responded when the monkey saw the experimenter manipulate something with their hands. These neurons were also sensitive to the direction of movement and the hand used to perform the action, suggesting that they are coded towards very specific movements and interactions.

An interesting finding in this study was that the mirror neurons only responded to actions which had a goal, not just to hand movements. Gallese et al (1996) found that whereas the mirror neurons fired when the investigator was reaching towards an object with the intention of picking it up, they were not responsive when only the hand shape was produced. This would suggest that knowledge of the intention of a grasping or reaching movement is required for mirror neurons to respond, which is why it is only actions within the individuals own repertoire that result in activation of the mirror neurons. Neuroimaging research has been conducted on humans in this area and has found that when humans observe an action within their repertoire, for example lip smacking behaviours, activation in the pre motor cortex occurs. However, when observing an action that isn't within their repertoire activation occurs in the visual cortex but not in the premotor cortex (Buccino, Lui, Canessa, Patteri, Lagravines, Benuzzi, Porro & Rizzolatti, 2004). This occurs because although the action is visually processed, there is no corresponding motor action represented in the motor cortex therefore motor activation doesn't occur. These findings provide support for the idea of mental representations of events and actions, which will be discussed later in this chapter.

Behavioural research into human behaviour has also found evidence of motor resonance when observing actions performed by others. Ambrosini, Constantini and Sinigaglia (2011) investigated this by observing anticipatory eye movements in participants watching another pick up an object. When performing visually guided actions, individuals will perform anticipatory eye movements by focussing on the first location before picking up the object and then focusing on the second location before placing it down. These actions are performed in order to effectively guide the movements by processing the spatial localities of the two desired locations and the exact parameters required for action (Flanagan and Johansson, 2003). However, research has shown evidence of similar eye movements when observing someone else performing the action. Ambrosini et al (2011) studied the eye movements of participants watching an actor reach towards an object in a scene containing another object. They found that when the actor reached with a specific hand shape compatible with one of the objects, observers performed earlier and more accurate eye movements towards the correct target object compared to trials where the actor merely reached towards an object. These findings suggest that the preshaping of the hand communicates sufficient information regarding the intended object to the observer to enable them to accurately match the hand shape to the mental representation of the objects, thereby facilitation correct target object identification.

Mirror neuron research has shown that observing an action being performed automatically activates the area in the brain associated with performing that action, suggesting that the same mechanisms are used for both understanding, observing and performing actions (Gallese, et al 1996). However, research into mirror neurons have identified two very different types of mirror neurons- “strictly congruent mirror neurons”, which fire when the action being observed matches identically to the action represented by the neuron, for example picking up an object using a power grasp, and “broadly congruent mirror neurons” which fire when the action matches the represented goal action, for example grasping, but is not specific about the way in which this action can be achieved (Gallese, et al 1996). The discovery of these two categories of mirror neurons has led to the conclusion that the mental representations of actions do not only code the movements themselves but also the goal of these movements (Craighero & Zorzi, 2012). Support for this finding comes from brain imagery research. Research into two individuals with aplasia who were born without hands and legs has found activation in the motor areas associated with other movements upon viewing of a range of hand movement (Gazzola, van der Worp, Mulder, Wicker, Rizzolatti & Keysers, 2007). Participants were required to watch a series of movies depicting hands manipulating objects along with static images of the hands not interacting with the object but resting behind it. The results found the same cortical area activations when the patients interacted with the objects with their feet and mouths as when observing the objects being manipulated with their hands. This suggests that in these individuals, the mirror neurons are activated according to the goal of the action, regardless of the effector being used to complete the action. The reason for this may stem from the interactions that aplasic individuals have with typically developed (TDs) individuals on a day to day basis. When interacting with TDs, the foot and mouth actions of the aplasic individual will often be performed alongside the hand actions of the TD, resulting in an association between the observation of hand actions and the simultaneous activation of foot and mouth areas within the cortical system (Gazzola et al 2007). These findings suggest not only that the mirror neuron system may be involved in goal matching as well as action matching but also demonstrates the plasticity of the mirror neurons themselves.

The results found in the previous study are attributed to the fact that aplasic individuals substitute hand use with foot use on a regular basis, resulting in a reorganisation of their neural system. However, research has also shown that observing a hand action is sufficient to prime a foot response in even healthy individuals. In a study by Craighero and Zorzi (2012), participants were required to watch the experimenter reach towards an object in front of them with either a compatible or incompatible grasp size and respond with either a hand or foot response when they think the experimenter will come into contact with the object. For half of the experiment, participants had their hands bound and for the other half they were unconstrained. Canonical neuron research has shown that observation of an object automatically activates the appropriate response codes required to interact with it, therefore participants in this study should, once they have visually processed the object, be able to predict the appropriate grasp for interacting with the object (Craighero, Bonetti, Massarenti, Canto, Fabbri Destro & Fadiga 2008). The researchers found that when the grasp size was congruent with that expected by the observer, the time-to-contact judgement was more accurate than when the grasp size was incongruent. However, they also found difference in the accuracy of responses according not only to grasp size but also to response type. The results showed that hand responses were most accurate when the hands were unconstrained, even though the constraint did not influence the ability to respond, whereas foot responses were most accurate when the hands were bound. The results of this study suggest that when the hand was primed and free to move, the Motor Priming Effect primarily targeted the hand, resulting in facilitated responses using the hand when the grasp used and the predicted response was congruent. When the hand could not be targeted, the effects were transferred to another limb, in this case the foot. The results of both this and the aplasic individuals studies suggest that when a primed movement is unavailable either temporarily or permanently, the mirror neuron system is capable of identifying the goal of the action without limiting it to a specific motor area, resulting in the achievement of the goal through other less traditional methods.

1.2 Simulation

The research into canonical and mirror neurons has led to the conclusion that observing an object or an action being performed automatically activates the associated physical actions, making them more readily available when subsequent performance is required (Murata et al, 1997; Gallese et al, 1996). This automatic activation of the appropriate actions means that the actions are effectively covertly performed with our minds, with the same neural activations occurring if the action was physically performed but minus the overt action. This covert performance enables us to not only understand what is presently occurring but also predict what the likely result is. For example, in Ambrosini, Constantini and Sinigaglia's (2011) study, by mentally performing the reaching action within their mind, participants were able to correctly match the hand shape of the actor to the correct object. This process of covert action is known as Simulation and forms the keystone of the current Embodied Cognition theory.

Traditional theories of cognition suggest that our knowledge and understanding of the world is contained within our Semantic memory system, which works independently from the systems involved in perception, action and introspection (Barsalou, 2008). Embodied Cognition, however, proposes that these systems work together to create multimodal representations of events that are integrated across all of the sensory modalities. When we encounter a situation or an object, in order to understand how to interact with it appropriately, we access these representations and re-enact, or "simulate", previous interactions in our minds, without performance of any overt movements. This re-enactment leads to the motor resonance effect described in the previous section. These simulations are required to enable us to interact appropriately with the world around us as we use previous experiences to help us understand situations that we encounter and predict what is likely to occur in the future.

Two stages of Simulation

Barsalou (2008) describes simulations as a re-enactment of the sensory motor experiences and introspective states that have been attained during interactions with the world, our body and our mind. According to Barsalou (2008), the process of simulation takes part in two stages- first is the creation and storage of the multi-modal representation, or concept, of an object or event that contains information gained through previous experience with the entity regarding perceptions, actions, mental states such as the motivations and intentions that govern the interaction, and the situational information about the environment in which these situations occur/ed. When an interaction is experienced, the neural systems are automatically activated that correspond to the event; for example, the motor system will be activated representing movements that occur, along with other sensory information such as sounds and smell (Barsalou, 2008). These activations are recorded and stored within the concepts and are integrated with the other sensory information. The result is a comprehensive set of representations that represent the event from many different perspectives and environmental settings and are ready to be accessed when the interaction occurs again (Yeh & Barsalou, 2006). These representations are not presented in isolation; rather they are situated within corresponding events and backgrounds. The appropriate representations are activated and processed depending on the specific situation in which the individual is in. If an action has either not been experienced before or is not in ones repertoire of actions, then we would have no representation of this behaviour in which to base future actions on. This would therefore explain why activation of the mirror neurons only occurs when observing an action that has been performed before (Barsalou, 2003).

Once the concepts have been created, the second stage of simulation takes place- the re-enactment, or "simulation" of the concept. In order to accurately understand the nature of an action, its mental representation is automatically accessed which contains all of the sensory-motor information regarding previous encounters with that action, as well as introspective information such as the motivation and goals of the action. When representations of events or objects are accessed, the neurons that were responsible for processing all of the sensory-motor information in its previous encounters will reactivate, resulting in an activation of the visual features of the object and any motor and mental states associated with it (Barsalou, 2003). These activations result in the mental re-enactment, or simulation, of the event as it previously occurred, complete with sensory-motor information related to the interaction. For example, observing a football will result in accessing the mental representation of a football which will include information of previous interactions, in order to determine what it is and what the appropriate course of action is. This will result in activation of the motor areas associated with previous interactions or observations with a football, such as a foot and leg movement, along with any introspective associations associated with previous experiences, such as elation when scoring a goal, resulting in a mental simulation of the process of kicking a ball. By accessing the mental representation and simulating the movement, the individual is then able to understand what a football is and what the appropriate motor action is. Simulation of the interaction will enable the individual to predict what is happening and what the likely outcome will be based on previous sensory-motor experiences, thereby modulating how they should behave in the situation (Barsalou, 2003). It is important to note, however, that the simulations of actions differ in a significant way from the physical performance of actions in that execution of the action does not take place. An explanation for this can be found in brain imagery research. Evangeliou, Raos, Galletti and Savaki (2009) found that the activation in areas involved in action execution is 50% weaker during simulations compared to during actual action execution, which suggests that simulation alone is not sufficient to result in the execution of an action. This in turn suggests that mental simulations are the rehearsal of actions minus the desire to perform.

Mental representations contain information about the affordances of an object and guide the individual into interacting with an object as appropriately as possible. They do not, however, contain all affordances for an object, only those that are appropriate for the task at hand. In a study by Borghi (2003), participants were required to perform imagery tasks using objects that they had to imagine themselves or others acting upon, building or seeing, such as a washing machine, bicycle and hi-fi, and then were asked to produce a list of the parts of these objects. The results found that the parts recalled differed depending on the imagery task that they were required to perform. The parts required for acting upon the object were recalled first in all conditions, which suggest that all of the objects were processed in terms of the potential interactions that could be performed with them. However, in the building and visual conditions, the parts recalled earliest in the list were all relevant to the visualisation task that was performed. These findings suggest that when events are simulated, different concepts are activated according to the goal of the individual, resulting in different affordances being activated in line with the required aim of the individual.

Mental and Motor imagery

The simulation of actions can be both unconsciously or consciously performed. In most cases, we are unaware that simulations are taking place as they occur automatically and therefore do not enter our consciousness (Barsalou, 2009). However, when a simulation becomes a conscious event, it becomes known as mental imagery. Mental imagery is the process by which an image is created in the mind to aid understanding of an event or situations in much the same way as a simulation would. These mental images usually contain spatial properties which are proportionate to the real life setting but don't contain any motor based information (Zwaan & Madden, 2005). For example, when describing the route to get to an unknown place, a mental image of the surrounding area will be summoned in order to enhance understanding and this image will usually be spatially accurate and contain details of the area. These images will include information that has not been specifically stated to the individual but will be constructed due to previous experience through mental representations.

The type of imagery used when performing simulations of actions and behaviours is known as motor imagery and it is this type of imagery that is of most interest to this thesis. Motor imagery is the conscious or unconscious simulation of actions covertly performed in the mind without the accompaniment of any overt action performance (Jeannerod, 1995). The main difference between motor and mental imagery is that whereas mental imagery focuses on the environment in which the individual is in, motor imagery concentrates on the kinaesthetic aspects of movements (Gaggioli, Morganti, Walker, Meneghini, Alcaniz, Lozano, Montesa, Gil & Riva, 2004). Individuals performing motor imagery tasks typically imagine themselves or others performing specific motor actions and represent the body as an active agent within the world causing changes (Jeannerod, 1995).

These covertly executed actions are shown to suffer from the same constraints as overt physical actions. In an early study by Georgopoulos and Massey (1987) participants were required to mentally rotate a manipulandum at an angle and in a direction specified by prior instructions that were either congruent or incongruent with that specified by a visual stimulus. The results found not only that reaction time was facilitated when the direction of movement was compatible with that indicated by the visual stimulus, which suggests that processing of the direction automatically activated a compatible physical movement, but that reaction times, which Georgopoulos and Massey (1987) considered representative of the mental movement time, increased linearly with the rotational angle, which is consistent with the results found when performing the action physically. A similar study was conducted by Decety and Jeannerod (1996) using virtual reality situations. In this experiment, participants were required to imagine walking along a path and through a gate that varied in width. Decety and Jeannerod (1996) found that mental walking time increased as the distance between the start point and the gate increased and as gate width decreased, which is consistent with real life performance. In a further study, they found that when required to imagine walking along beams of differing widths, response times increased as the widths decreased. This is indicative of the Fitts law theory of a speed-accuracy trade off typically found in physical actions, which demonstrates an inverse relationship between the difficulty of performing a movement and the speed at which it can be performed, with increased reaction time as difficulty increases (Fitts, 1954). The findings of these studies suggest that motor imagery is subject to the same physical constraints as physical motor actions and therefore modulators of movement, such as those postulated by Fitt's Law, are employed not only when movements are executed but also during the planning phase. These findings have led to the conclusion that motor imagery is performed using the same mental mechanisms as overt physical movement.

Mental rotation is frequently used as an example of motor imagery. The link between motor action and mental rotation of objects has been extensively investigated using both behavioural studies and brain imaging techniques (Shepard and Cooper, 1982; Wexler, Kosslyn and Berthoz, 1998). Shepard and Metzler (1971) suggest that many of the same processes are involved during the mental rotation and physical rotation of objects. In their pivotal study, participants were presented with pairs of abstract 3D objects portrayed at varying degrees of rotation and were required to decide as quickly as possible whether the objects were the same or mirror images of one another, as shown in Figure 1.1.

The results indicated a linear relationship between mental rotation time and rotation angle, with smaller response times for smaller angles of rotation and larger response times for larger angles. These results not only suggest that rotation is taking place but also that mental rotations are executed along similar constraints as physical rotations, with longer time taken for larger angles of rotation, providing support for a relationship between motor action and motor imagery. Wexler et al (1998) propose that the mental rotation of an object is a simulation of physical

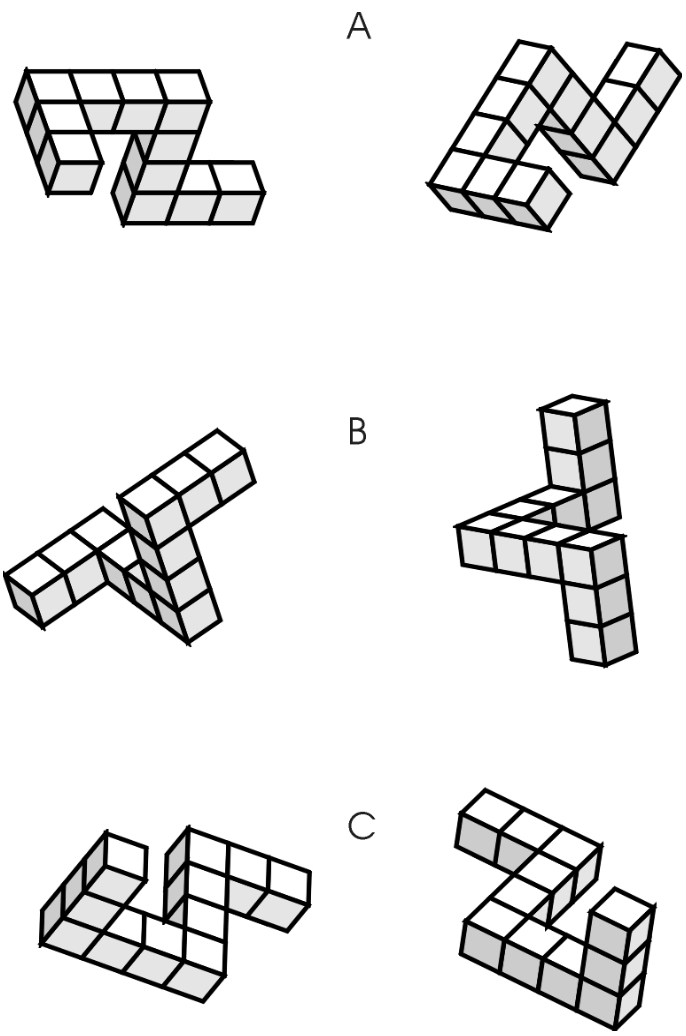


Figure 1.1: *The mental rotation task designed by Shepard and Metzler (1971) demonstrating (a) & (b) same shape and (c) mirror image as used by Hesslow (2002). Permission to reproduce this image has been granted by G.Hesslow.*

motor rotation, involving the planning of motor actions but not the execution of such actions. Support for this theory comes from brain-imaging studies. During performance of the Shepard and Metzler (1971) task, activation has been found in areas associated with physical action preparation, such as the superior parietal lobe, lateral premotor areas, supplementary motor area, as well as low level cortical motor activation (Richter, Somorjai, Summers, Jarmasz, Menon, Gati, Georgopoulos, Tegeler, Ugurbil & Kim, 2000; Wraga, Boyle & Flynn, 2010). Richter et al (2000) propose that activation in these areas is the direct result of the performance of the mental rotation, which suggests that the mental rotation of objects involves simulation of the physical activity, resulting in activation of the same brain areas associated with physical action without execution of the action taking place.

Research into the link between motor imagery and motor performance has shown that physical execution of an action during a motor imagery task can have a significant effect upon performance. Wexler et al (1998) found that when performing the Cooper and Shepard (1973) 2D image rotation task, participants were faster when performing a physical motor rotation task in a direction compatible with the mental rotation task. In this experiment, participants were presented with a 2D abstract object and were required to judge as quickly and accurately whether it was identical or a mirror image of an object presented after a short interval, during which participants were informed of the orientation of the subsequent object. This was designed to manipulate the direction in which the first object would be mentally rotated. During this stage, participants were also required to rotate a joystick in either a congruent or incongruent direction to the mental rotation. Judgements were faster and more accurate when the direction in which mental rotation was performed was compatible with the direction in which the joystick was rotated. The results also showed that manipulation of the speed of motor rotation directly influenced the speed of mental rotations, with slower mental rotations during slow physical rotations and faster mental rotations during faster physical rotations. These findings suggest that motor actions and motor imagery share the same neurological processes, therefore the performance of a motor action during mental rotation can interfere with the mental rotation if similar action codes are activated, lending support to the proposal that mental rotations are directly coupled with motor actions.

Motor Imagery and the Body Schema:

Research into motor imagery has demonstrated the similarity between mentally simulated actions and those that are physically executed in terms of not only the motor areas activated when performing them but also the physical constraints that determine both movements (Wexler et al, 1998). This would suggest that mental representations not only contain information about the actions associated with an object but also how our body is physically capable of performing those actions. As healthy individuals, we are capable of performing complex bodily movements without constant visual updates on the position of our body (Schwoebel, Friedman, Duda & Cosley, 2001). For example, rotating hands to the left and right can be done with the same ease with our eyes closed as with them open, suggesting the existence of an online mental representation of our current body posture. Head and Holmes (1911) were the first to propose the existence of an online representation of the body, or body schema as it is more formally known, which contains sensory information obtained from current interactions which in turn results in an up-to-date (and therefore continually changing and adjusting) representation of our body in relation to itself and the environment around it. Head and Holmes (1911) also suggested that the body schema is involved with the guiding of movements through interactions with the motor system. The Embodied Cognition theory highlights the importance of the relationship between the sensory-motor areas and perception in the mediation of movements and research into this relationship has indeed shown that everyday movements are significantly impaired in patients with sensory deficits, who are only able to partly compensate for this deprivation through the use of constant visual guidance (Cole & Paillard, 1995). When moving within our environments, we use the constant sensory information not only to inform us of what we are currently doing in terms of body positioning but also to enable ourselves to plan and execute future actions by updating our current positioning within the world. Those individuals who are unable to integrate their sensory information with their perceptual information have a largely impaired and inaccurate body schema and are therefore left to rely upon perceptual information alone in which to guide their interactions. An extreme example of this would be the optic ataxia patients described in the previous section- these patients are unable to integrate their visual and motor information and therefore were unable to interact appropriately with objects in the environment as they were unable to determine whether their movements were appropriate for the object they were trying to interact with (Jeannerod, 1986). Schwoebel et al (2001) suggest that the only partial compensation shown in individuals with sensory deficits demonstrates both the importance of sensory feedback in the planning and execution of actions and the strength and importance the role the body schema has in the control and guidance of movement.

Head and Holmes (1911) originally proposed that the body schema is chiefly involved in the monitoring and updating of the body position in order to perform actual physical movements. However, research suggests that the body schema also plays an important role in motor imagery and the simulation of actions. Parsons (1987 a, b) proposed that when required to make judgements about the positioning of body stimuli, for example judging the laterality of hands or feet, participants simulate movement of their own body part until it falls in line with that in which they are observing. As a result, Parsons found that the current positioning of participants own hands influenced the reaction times when responding to such stimuli. In Parsons' (1994) study, participants were required to make a laterality judgement of hand stimuli presented in a palm upwards orientation. Parsons found that not only were response times longer when the participants' hands were in a palm down compared to a palm up orientation, but response times were significantly longer as the angular disparity between the test stimulus and the participants hands increased. Parsons (1994) suggests that when making these judgements, the current positioning of the participants hands was taken into account, even though it had no explicit role in the task, which in turn suggests that the body schema is not only involved in real bodily movements but in imagined ones as well.

Further support for role of the body schema in mental simulation of movements is provided by studies exploring the effect of constraint on the mental rotation of body parts. In the Shepard and Metzler (1971) paradigm, the objects do not possess any constraints in themselves, i.e. each shape is perceived as easy to rotate as the next. Body parts, however, have constraints in terms of their physical execution, which research has shown can influence mental rotation. When mentally rotating body parts, rotation is easier when done in a way compatible with the real life rotational abilities of that body part (Cooper & Shepard, 1975; Parsons, 1987). In Cooper and Shepard's (1975) study, participants were required to identify presented hands that had been rotated as either left or right. Mental rotations were more accurately performed and response times faster when the mental rotation required for transformation was in keeping with comfortable real life rotation abilities. These results suggest that as the uncomfortable or impossible rotations are not part of the individuals repertoire, the individuals will be unable to use the information contained their body schema to complete the task and are therefore less successful at predicting what the outcome of the rotations are, as demonstrated by the higher error rates and slower rotations in the uncomfortable compared to the comfortable rotations. Similar effects have also been shown for the rotation of objects manipulated using body parts. When asked to determine whether a screwdriver was screwing or unscrewing, response times were significantly longer when the screwdriver was presented at an uncomfortable orientation for the participant's handedness (De'Sperati & Stucchi, 1997). For example, right handed participants were slower at responding when the stimulus was orientated in a left handed position compared to right hand compatible orientations. When asked to explicitly imagine that their hands were manipulating the screwdriver, similar results were found when using their right dominant hand. When asked to imagine grasping with their left hand, however, general response times increased and the difference in response times between comfortable and uncomfortable orientations disappeared. These results suggest that when mentally rotating the screwdriver, simulated movements using the dominant hand were employed which resulted in facilitation effects in comfortable trials and right hand imagined trials. In left hand imagine trials, however, participants created a simulated movement using a non-dominant hand which, being an unfamiliar movement, resulted in a less efficient motor simulation, as demonstrated by the increased response times across both the comfortable and non-comfortable orientations.

Neuropsychological research has shown that mental rotation of body parts automatically activates the neurons associated with the physical performance of those movements, resulting in activation of the associated body parts and increased readiness to perform that action (Kosslyn, Digirolamo, Thompson & Alpert, 1998). In their study, participants were presented with 2 images of a hand and were required to respond regarding the laterality of the hand on the right hand side of the display. Brain activity was measured throughout the experiment. The results found significant activity throughout the motor areas of the brain, including the pre motor cortex and primary motor cortex. These findings suggest that in order to perform the mental rotation of body parts, the brain areas associated with those actions are activated, resulting in the covert mental simulation of those actions. These findings are consistent with those found during the mental rotation of objects and suggest that both the planning and execution of actions involves the same neural activations.

Real life applications of these findings have found that motor imagery of body parts can be used as an effective recovery technique to trigger reorganisation in the cortical area and also enhance recovery times in patients suffering from a stroke. In a study by Johnson-Frey (2004), 3 severely hemiplegic patients completed daily practice of computer based motor simulation tasks over a 9 week period. Prior to this period, patients had suffered from loss of use in their non-dominant arm for a range of 1 to 5 years as a result of severe strokes that damaged their motor circuits. During their recovery program, the patients were required to perform and imagine a combination of simple and complex finger movements with both their paralysed and non-paralysed arms, coupled with other simulation based tests such as hand laterality judgements. The study found that after completion of the rehabilitation program, one patient, who had been unable to move his right arm and hand for 5 years, demonstrated an increase in activations in the parietal, motor and supplementary motor areas associated with the damaged limb, which suggests that motor simulation can facilitate the reorganisation of neural networks within a severely damaged brain area that has previously shown no signs of improvement. Contrasting studies, however, have found that the performance of mental practice alongside motor imagery techniques is not sufficient to stimulate recovery in early stroke patients, which suggests that mental imagery alone may not be sufficient to encourage reorganisation of neural networks, rather their success may be the result of a combination of both physical and mental practice (Ietswaart, Johnston, Dijkerman, Joice, Scott, MacWalter & Hamilton, 2011). These findings therefore suggest that the use of motor simulation alone as a rehabilitation technique needs to be approached with caution, however the results of these studies suggest that the motor activations caused as a result of mental simulation of actions can help aid the recovery of brain damage related motor inability.

1.4 Motor constraints and simulation

The Embodied Cognition theory emphasises the bi-directional relationship between our actions and our cognitions, in particular how our perceptions and mental state can influence our actions. However, one of the main points of interest regarding the Embodied Cognition theory is that the experiences that facilitate the development of our cognitions are dependent not only on the environment in which we are in but also the physical ability of the individual. This leads us to the main question that will be investigated in the rest of this thesis- if our cognitions are dependent upon ability, what effect do short term physical constraints have on our performance of cognitive tasks that have a motor component, such as motor imagery? The Embodied Cognition and simulation theories have demonstrated that the same neural networks are employed for both imagery and action processes, therefore one should expect that changes to our bodily capabilities could influence the way in which we perceive events. This section will review the research currently in this area and will introduce the research question for this thesis.

Injury and simulation

The research in the previous sections has discussed how the mental simulation of actions can be influenced by concurrent performance of compatible or incompatible actions. However, there is research to suggest that simulation itself can have negative effects on the body's performance. Research into mental illnesses such as depression has shown that our thoughts and moods have a motor component which can affect the physical performance of the individual. Depression is a mental disorder often triggered by the occurrence of negative events in one's life coupled with the beliefs that these events are likely to be persistent and will have roll on effects on other important areas (Lindeman & Abramson, 2008). Sufferers often feel powerless to change their fate and are therefore demotivated to try, resulting in a number of negative physical symptoms such as low energy and delayed motor movement, otherwise known as psychomotor retardation. Research into motor simulation suggests that these physical symptoms are the result of a metaphorical mental simulation of physical incapacity (Lindeman & Abramson, 2008). In depression, sufferers often experience feelings of hopelessness in relation to important aspects of their life and feel that they are powerless to make a change. Gallese and Lakoff (2005) suggest that the mental representations of abstract states such as hopelessness often include sensory motor simulations, much like mental simulations of movements, however in these examples the simulations are often metaphorical rather than the result of previous experience as in action representations. For example, the verb "grasp" can mean to take hold of something physically and also intellectually and both events are accompanied by a sensory motor simulation of grasping an object, resulting in activations in the motor areas responsible for carrying this action out physically (Gallese & Lakoff, 2005). The concept of hopelessness, specifically the inability to alter the negative life events that have resulted in the depression, is conceptually linked to physical incapacity which in this case is metaphorically linked to the inability to bring about change (Lindeman & Abramson, 2008). It is the simulation of physical incapacity that research suggests leads to the delayed physical motor responses characteristic of psychomotor retardation. The existence of metaphorical simulations demonstrates the strong bond between our physical and psychological states. However, more importantly for this research, research in this area demonstrates that the simulation of being incapable of physical movement is sufficient to limit our actual movement capabilities without there being any physical reason for why movement is prevented.

Research has shown that constraints upon our physical capabilities, such as injury, can have a significant impact on our ability to perform mental imagery tasks. Mental rotation in general is typically used as an example of action simulation as the processes that occur during mental rotations are subject to the same constraints as physical rotations, making it an ideal example of the interplay between cognition and action. This direct link, however, also makes it useful for measuring strains in body parts in medical environments. Yamada and Mastumoto (2009) investigated rugby players with hamstring injury and found that their ability to perform mental rotations of images of their damaged limb was positively correlated to the level of damage that they were suffering, with longer reaction times for those that were suffering from the worst damage. As their strains healed, performance in the rotation task improved linearly with it. The investigators measured the strain using the participants' ability at performing the 90° mental rotation. In order to perform it physically, patients would have to extend their knee and internally rotate their hip, putting extreme strain upon their damaged hamstring. Even though no overt movement was actually required, participants were unable to mentally simulate the action as they were currently unable to perform it. This suggests that the body schema mental representation is continually updated in order to incorporate any physical restrictions that one may have and any actions and simulations that may occur will take into account this change in ability. This would imply that our mental simulation capabilities are influenced directly by our physical capabilities, which provides support for the assumption that mental imagery employ the same processes as overt physical movement and that any physical restrictions that occur will have direct impact on our simulation ability.

The previous study looked at the impact temporary physical injury can have on our ability to perform mental simulations; however research has investigated the effect that permanent loss of function in a specific limb can have on performance on motor rotation tasks involving that limb. Nico, Daprati, Rigal, Parsons and Sirigu (2004) investigated performance in motor imagery tasks in participants who had suffered the amputation of their dominant hands. Participants were presented with rotated images of left and right hands and were required to respond according to which hand was presented. It was predicted that participants who had lost their dominant hand would make significantly more errors in recognising this hand when presented than control participants. The researchers hypothesised that when making a decision, participants would be required to rotate the stimulus hand into its standard orientation, which would involve simulation, which in turn would result in activation of the appropriate motor limb. If motor imagery is possible without the physical presence of the motor limb, then amputees should be able to perform motor imagery as effectively as control patients. However, if mental simulation is dependent upon the physical condition of the body at that current time, amputees should be significantly impaired in performing mental simulations of the amputee limb and therefore will be impaired in the recognition of it. The results found that amputees made significantly more errors and were significantly slower when recognising their dominant limb compared to control subjects, which is in line with the experimenters' predictions. However amputees who had lost their non-dominant hand demonstrated no significant differences in responses compared to control subjects. The study was also performed with amputees wearing prosthesis in order to investigate whether visual mimicry of the body part affects motor imagery. The study found similar effects to the non-prosthesis study, with significant differences between amputees wearing the prosthesis on their dominant hand and control subjects, with significantly more errors and slower reaction times towards dominant hands compared to control subjects. Congenital limb disorders were also studied and the results found no significant difference in accuracy of responses compared to control subjects but were significantly slower in responding across all conditions. An interesting finding however was discovered regarding the orientation of the hands presented. As is consistent with previous research in this area, amputees and controls were significantly slower in responding to unnatural rotations compared to natural rotations. However, the results found that there was no effect of rotation degree when it was the missing limb that was presented in congenital limb disorder sufferers but there was a significant effect when the hand that was presented was their remaining limb. Nico et al (2004) suggested that this is due to a lack of experience of the postural constraints of the missing hand. Previous research suggests that in order to perform motor simulations, the movements being simulated must have been performed previously, or at least been experienced by the individual (Barsalou, 2008). When the limb is missing from birth, the individual will never have performed any action using that limb; therefore the motor simulations that are performed won't be subject to any postural or joint constraints, resulting in the smooth mental rotation as found here. The findings of these studies demonstrate that while loss of the limb may result in less accurate laterality decisions, especially when the amputee arm is dominant, it does not prevent laterality judgements in their entirety. Motor imagery still occurs when presented with the amputated limb, as demonstrated by the increase in response times when the rotation results in an unnatural end position, but the higher inaccuracy levels in amputees compared to controls suggests that motor imagery is disturbed by the loss of a limb. Nico et al (2004) suggest that this could be due to disruption to the performance of the neural networks that control motor simulation. Research has found that the current positioning of the limbs is communicated when performing a motor simulation as simulation is performed starting from the limbs initial positioning (Parsons, 1987 a, b). When motor imagery is occurring in amputees, the

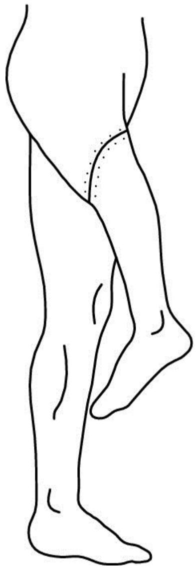


Figure 1.2. *A pictorial demonstration of a Vas Nes rotationplasty as demonstrated by Curte, Otten & Postema (2010)-Permission to reproduce this image has been granted by E. Otten*

motor codes for that limb are still activated but the flow of information regarding the positioning of the limb is unavailable, making simulation very difficult. As a result, participants may have used a visual-spatial approach rather than a motor approach when presented with the more difficult orientations, for example focusing on the positioning of the thumb in relation to the rest of the hand rather than rotating the hand in relation to their own. Simpler rotations could afford a more simple strategy such as matching the stimulus hand to their own. These findings would suggest that when motor imagery is unavailable, visual-spatial strategies will be used instead.

A similar study was conducted using a patient who had undergone a Van Nes rotationplasty, a very rare form of surgery used when the upper portion of the leg is diseased but the lower part is preserved (Curtze, Otten & Postema, 2010, see Figure 1.2). The leg is amputated from the thigh downwards but the lower leg is reattached to the body from the thigh at a rotation of 180° with the foot facing backwards and the ankle joint performing as the knee joint. In order to learn to walk again, the cortical representations of the leg must reform and adapt to the repositioning of the foot and this can only be accomplished through movement. Research suggests that mental imagery is sensitive to the actual positioning of body parts (de Lange, Hagoort & Toni, 2006) therefore the reverse positioning of the foot in this patient should influence laterality judgements of images of rotated feet. The stimuli consisted of a combination of line drawings of feet, from the original data set created by Parsons (1987), and photographs of real and prosthetic feet. The limbs were presented at varying degrees of rotation along the median line from both a dorsal and plantar view, with the 0° orientation being that with the toes facing upwards for the dorsal and the toes facing downwards for the plantar view. Responses were required according to the laterality of the foot, with left feet indicated with a left button press and right feet indicated with a right button press. If the current positioning of a limb influences subsequent motor imagery tasks, then the results should reflect this by showing increased accuracy and reduced response times when responding to stimuli representing the rotated limb presented in the plantar view, as this is consistent with the current positioning of the foot. Indeed, the results showed a slight trend in response times when the stimuli referring to the affected foot was presented in the plantar view, with faster and more accurate responses compared to the dorsal view of the same foot. These findings, however, were not significant, and suggest that even though the patient had adapted their movements to incorporate the new positioning and therefore one would assume that the cortical reorganisation had taken place in order to represent the change, the original orientation is still represented in the brain and it is this that is used when computing the initial position of the foot ready for motor simulation. This does not disprove the notion that simulations are concerned with the initial positioning of body parts, however, as Corradi- Dell' Acquaa, Tomasino and Fink (2009) propose the existence of two distinct body representations in the brain; the first concerns the typical body schema, which includes representations of one's own body and it's positioning in the environments, including the current positioning of body parts, whereas the second represents the structural positioning of the body parts on a prototypical body. Curtze et al (2010) suggest that it is the second representation that the rotationplasty patient is most likely using to perform the rotations. However, it is very likely that the removal or adjustment of the positioning of the body leads to such disruptions in the neural communications required for motor simulation that visual, rather than motor, transformations are used instead in these circumstances.

Artificial constraint and simulation

Previous research into amputations has demonstrated that amputees are still capable of performing mental simulation tasks involving the effected limb. These individuals suffered from permanent changes to their body, however research has found that temporary imagined paralysis can also influence body transformations. In a study by Hartman, Falconer and Mast (2011), participants were instructed to sit in a wheelchair and imagine themselves to be paralysed from the waist down whilst performing laterality judgements of imitable and non-imitable body postures. Participants were presented with images of individuals in yoga-like poses with either a bent leg in a natural position or in an unnatural position that is impossible to imitate and were required to judge whether the bent leg was left or right. The Embodied Cognition theory suggests that the natural postures are within the individual's repertoire and therefore should be easy to simulate, whereas unnatural postures are not and therefore visual-spatial based transformations are used instead (Amorim, Isableu & Jarraya, 2006). Mental representations of the body are constantly updated to take into account the body's current status (Gallagher, 2005) therefore if imagined paralysis influences our mental representation of our body, interference effects should occur when patients simulate imitable postures but not inimitable postures as they are not successfully embodied in a healthy individual. The results found that imitable postures took significantly longer to transform during imagined paralysis compared to a control condition where no imagery instructions were provided, whereas inimitable postures were not influenced by the imagined paralysis. Research in this area suggests that when performing mental transformations of body parts, the individuals imagine their own body part as that being transformed and therefore try to mentally replicate the posture with their own limb (Parsons, 1994). In those conditions where the action was not physically possible, this mental replication technique could not be implemented and therefore visual techniques were employed instead. The results of this study indicate that even when movement isn't physically restricted and is only imagined, mental simulation techniques are disturbed as the mental representation of the body has incorporated the paralysis into its schema.

Research has also found that the process of viewing someone else restricted is sufficient to interfere with simulation. Neuroimaging research has shown activations in the brain areas responsible for action upon observation of someone else performing an action (Gallese et al, 1996). Along with representations of actions, research has also found that contextual information regarding a situation, for example other people in the scene, is represented in the mirror system (Iacoboni, Molnar-Szakacs, Gallese, Buccino, Mazziotta & Rizzolatti, 2005). Liepelt, Ullsperger, Obst, Spengler, von Cramon and Brass (2009) suggested that if contextual information is mirrored and details of the physical condition of other people is represented, the observation of someone being restrained should lead to the same restricted effect in the observer. In order to test this theory, Liepelt et al (2009) presented participants with images of a hand with either the numbers 1 or 2 printed between the index and middle fingers. The images were presented from an egocentric perspective and featured restraint across the index and middle fingers, across the thumb and ring finger or no restraint at all. Participants were required to lift their fingers in response to the number that was presented, with an index finger lift to a "1" and a middle finger lift to a "2", therefore the pictured restraints either matched or didn't match the response fingers. If mirror neurons represent features such as the physical capabilities of others, we would expect to see increased reaction times when the restrictions match the response fingers, as the restrictions should be mirrored and therefore represented as restricted in the observer. The results indicated that a restriction effect did occur when the restricted fingers in the test picture corresponded to the response fingers, with significantly longer reaction times in those conditions, but there was no restriction effect when the stimuli showed the thumb and ring fingers restricted. These findings suggest that our simulated behaviours automatically represent contextual events and these influence subsequent performance of actions to bring them in line with the event processed. Brain imaging research has also supported this finding. In follow up study by Liepelt et al (2009) participants were again presented with photographs of left and right hands and were required to make a finger lift response regarding the laterality of the hands, using either a left or right index finger response in the index finger condition or a middle finger response in the middle finger condition. Participants were required to prepare their response upon presentation of the stimuli but had to withhold it until a second image was presented in which either the two index fingers or the middle and thumb were restrained. These restrictions were either compatible with the response required or incompatible. The lateralized readiness potential (LRP), a measurement of brain activity that indicates when a person is going to move, was measured in the participants as they prepared their response and the findings showed a distinct effect of restriction on the LRP results. A significant change was found in motor related LRP components when participants made a response using a finger that was clamped in the stimuli and this change was dependent on the amount of preparation that the participants had made before performing, with less preparation resulting in more effect of the restraint. Liepelt et al (2009) conclude that as the visual restriction was presented after the motor preparation had occurred, the presence of the restriction effect suggests that the restraint influences responses on a motor level rather than on a visual level. The results of these studies show that observing another individual being restrained is sufficient to mediate responses in line with the restriction. This provides evidence that individuals mentally represent the contextual effects within a situation, in this case action restriction, and reflect those effects onto the participant's representation of the event, resulting in changes to the motor representation in line with the constraints being observed and incorporation of the constraints into the mental simulation taking place.

The previous studies have shown how restricting motor movement can influence our ability to perform motor imagery tasks. Research has found, however, that temporarily constraining motor ability can also influence action observation. When reaching towards an object, our gaze automatically shifts between our hand and the object that we are reaching towards in order to aid the planning and execution of the action. Similarly, when observing someone else performing this reach, we make very similar eye movements in order to correctly estimate which object is being reached for (Ambrosini et al, 2011). Ambrosini et al (2011) found, however, that when the observer was unable to perform the observed action, their ability to judge the intended target object diminished. In their study, participants were required to watch an actor reach towards and pick up one of two potential target objects which differed according to the grasp size required to pick them up. In a control condition, the actor merely reached towards and touched the object with his fist. In the grasping condition, the actor formed his hand into the appropriate hand shape from lift off. Participants performed half of each condition with their hands tied behind their back and were simply required to watch the video. The results found that during the experimental condition, the participants' planning gaze behaviour was significantly impaired when their movement was restricted, compared to trials when they were free to move. In the unconstrained condition, participants were able to accurately and swiftly determine which object was the intended target, however when constrained, participants took significantly longer to make the correct choice. Ambrosini et al (2011) suggest that an explanation for this behaviour can be found in the mirror neuron research. When observing someone reaching towards an intended target, we employ the same mechanisms that we would use if we ourselves were planning to perform the reach, i.e. access the mental representations of that object in order to determine the appropriate action and grasp size to interact with the object and perform gaze shifts between the hand and target object. By constraining the motor ability of the participant, they are impaired at planning the appropriate action, and are therefore impaired at determining the target object, resulting in increased reaction times in the constrained condition. The results of this study indicate that our ability to observe other peoples actions is directly related to our own physical capabilities and that temporary inhibition of movement is sufficient to disrupt our ability to plan and observe actions.

The previous studies have looked at the effect of constraining actions on performance on motor related tasks; however research also suggests that extending our bodily capabilities can have a significant effect on our performance in these tasks. Witt, Proffitt and Epstein (2005) investigated the effect of artificial reach extension on the ability to judge the distance of an object. In their study, participants were required to judge the distance of a dot that was projected in front of them and then either reach out and touch the object if it was in their peripersonal space, i.e. within arm's reach, or point to the object if it was in their extrapersonal space, i.e. out of reach. Participants performed half of the trials using a conductor's baton to perform their reaches; the results indicated that when the baton was used, the targets that were located in the extrapersonal space but reachable using the baton appeared closer to the participants compared to in trials when the baton was not used. The results of this study indicate that when the baton was used to extend the reach of the individual, their body schema adapted to take into account this extension thereby changing the individual's perception of both their reaching capability and the distance of the object, making objects appear closer. Bertini and Frassinetti (2000) found similar results in a patient suffering from neglect. In their study, Patient P.P was required to perform a line bisection task in both their peripersonal and extrapersonal space using either a laser pen or a stick. When the task was performed with the laser pen neglect was demonstrated in the peripersonal but not extrapersonal space, however when the task was performed using the stick neglect was found in the extrapersonal as well as peripersonal space. The results of this and the previous study suggest that when a tool is used to extend an individual's reach, the area that is reachable when using the tool is remapped to become peripersonal, resulting in objects in those areas appearing nearer and in-reach. This suggests therefore that our body schema automatically updates our physical capabilities to include not only detrimental changes but also enhancements which may influence our ability to interact with items in our environment. These findings demonstrate that changes to an individual's action capabilities can have a significant impact on perceptual judgements compatible with those manipulations.

This section looked at the effect that temporary and permanent motor ability manipulations can have on performance of tasks with a motor component, such as motor imagery. According to Embodied Cognition research, our cognitions and perceptions are influenced by our interactions with the world and are mediated by the constraints that both the environment and our body enforce upon us. The research reviewed in this chapter has demonstrated not only the roles that our cognitions and body play in the preparation and execution of actions but also the impact that both temporary and permanent inhibition of action can have on our ability to perform certain cognitive tasks. The aim of this thesis is to investigate the extent to which our motor abilities influence our cognitions and to explore the effect of temporary motor restriction on our ability to perform both basic and more complex action-relation cognitive processes, with a focus on the potential implications of this to the theory of Embodied Cognition.

1.5 Overview of Experiments

The main purpose of this research was to investigate the link between the current physical capabilities of the body and our ability to perform certain cognitive tasks which had a motor component, specifically the mental simulations of actions. Research into the mental simulation of actions has demonstrated that changes to our motor ability, be it through experimental manipulation or injury, can have significant consequences on our ability to perform mental simulations of actions (Parsons, 1987 a, b). When performing a mental simulation of an action, motor information from the mental representation will be included along with information from the body schema regarding up-to-date bodily information. As a consequence of this, changes to our ability to perform specific action should therefore be represented in any subsequent mental simulations of those actions. The aim of this thesis was to investigate whether the restriction of a motor action has a significant effect on the performance of mental simulations involving those actions and also to investigate the extent of the role of the body in these situations. Full Ethical clearance was obtained for all other experiments in this thesis.

Previous experiments investigating the effect of changes to physical capability on simulation ability have typically focused on postural effects during the mental rotations of body stimuli, therefore this thesis aimed to investigate the effect of restriction on a number of different cognitive tasks involving action simulation. It was predicted throughout this thesis that the restriction of performance of compatible actions and movements will significantly disrupt the mental simulation process in these tasks, resulting in significant differences in response performance and accuracy between restricted and unrestricted conditions. If this occurs, then it can be concluded that current motor abilities are directly related to our cognitive ability in these tasks. However, if differences occur regarding the effect of action restriction between these types of simulations then it can be concluded that different bodily and cognitive processes are required for successful completion of these tasks, which would have significant implications regarding our understanding of the role of the body in cognitive tasks such as these.

The experiments in this thesis focused on three different types of mental simulation tasks in order to investigate whether different processes and bodily contributions are involved in the different simulations. These tasks included simulations that occur unconsciously as the result of motor resonance through the observation of manipulatable objects; simulations that occur during performance of mental transformations of manipulatable objects and body part stimuli; and simulations that occur consciously through the observation of actions performed by another individual. Based on previous mental simulation research, it is predicted that action restriction will significantly affect performance in all of these types of simulations (Parsons, 1994; Ambrosini et al, 2011, Craighero & Zorzi, 2012). However, if differences occur regarding the effect of action restriction between these types of simulations then it can be concluded that different bodily and cognitive processes are required for successful completion of these tasks, which would have significant implications regarding our understanding of the role of the body in cognitive tasks such as these.

The first series of studies for this thesis looked at the effect motor restriction on the ability to process simple object affordances and aimed to establish whether temporary constriction of movement disrupts the ability to identify and process action related properties of objects through incorporation of the restriction into the action simulation. Extensive research has been conducted into the areas of affordances and micro-affordance and their relationship to our general abilities (Ellis and Tucker, 2001) but very little has focused on whether affordance detection can be influenced by changes to our specific abilities. In this context, the term "general abilities" refers to the actions and abilities that are in ones repertoire when not constrained by temporary limitations or impediments. "Specific abilities", in contrast, are subject to these obstacles and refers to the actions and behaviours that a person can exhibit at this particular given time (Ambrosini, et al, 2011). Three paradigms were used to investigate whether action restriction can disrupt affordance communication- the first paradigm investigated the effect of action restriction on conscious affordance retrieval, whereby participants responded to the handedness of household tools. The second paradigm used an object Temporal Order Judgement (TOJ) design to investigate the effect of restricting hand actions on the active object bias typically demonstrated in these experiments (See Chapter 2 for a review of this research). The final experiment in this series used an object based Simon effect design in order to investigate whether restricting hand movements would disrupt participants ability to process the handedness of objects and therefore remove the stimulus response compatibility effect found in these studies.

If significant differences are found in these experiments between restricted and unrestricted conditions, this would suggest that the current ability to perform an action is directly related to our ability to perceive the affordances of objects.

The second series of experiments aimed to investigate whether the restriction of actions disrupted the mental rotation of objects. This series of experiments were similar to the paradigm first developed by Shepard and Metzler (1971) in which participants were presented with 2 abstract shapes rotated at different angles from each other and were required to judge whether they were the same or mirror images. In these experiments, participants were presented with two shapes rotated at differing degrees from each other, framed as being a 3D manipulatable object and an aperture that the object had to fit into. 3D objects were used so as not to afford any specific actions other than a grasping and transportation action so as to avoid any conflicting action activations that may influence the simulations. Motor imagery research suggests that mental rotations of objects are performed by conscious mental simulation of a physical rotation of an object using the limb typically involved in interaction with that object (Richter et al, 2000). These simulations not only result in the same motor activations as when performing those actions physically but they are also constrained by the same physical restraints (Cooper & Shepard, 1975; Parsons, 1987). As a result of this, it is predicted that restricting hand movements should disrupt the mental simulation process, resulting in significant differences between rotation ability and accuracy in the restricted and unrestricted conditions. If this occurs, then this would suggest that information regarding current physical ability is incorporated into the mental rotations of object, which would in turn suggest the ability to perform an action corresponding to the mental action being simulated is required for accurate simulations.

The third series in this thesis investigated the effect of restriction on the ability to perform mental rotations of hand stimuli. Research into body part rotation has shown that the posture of our own hands interferes with our ability to perform mental rotations of hand images, which suggests that information regarding the current positioning of hands is required for accurate mental rotation ability (Parsons, 1994). This would suggest that some information up to date limb information is required for accurate mental rotations, therefore this series of studies investigated the effect of restricting hand movement on the mental rotation of hand stimuli. Research into the mental rotation of body parts has found that these transformations are typically performed by mentally transforming the position of one's own body part in order to bring it into line with the experimental stimuli, resulting in activation in the motor areas involved with that movement (Parsons, 1994). This type of conscious motor imagery has been found to be disturbed by changes to physical ability such as muscle strain, therefore this series of experiments aims to investigate whether temporary restrictions to the physical capability of the hands to make them incapable of performing the corresponding motor action disrupts the mental rotation of this stimuli. If there are significant differences between restricted and unrestricted conditions, this would suggest not only that current physical ability is incorporated into the mental simulations of these actions, but could also suggest that the postural effects found in previous hand rotation studies could also be the result of the prevention of movement disrupting the simulation process.

The final series of experiments investigated whether hand restriction would disrupt the ability to make motor based judgements of other peoples actions. This series of experiments used a Time to Contact paradigm in which participants had to judge the time at which they predicted an actor would come into contact with an object. In this study the speed of reach was manipulated and participants did not witness contact being made at any point, therefore in order to make an accurate judgement it is predicted that participants would have to mentally simulate the reaching action and incorporate any performance information into it. Research has shown that when we observe another individual performed an action (with a goal) the motor areas associated with that action are activated, resulting in increased readiness to perform that action (Gallese et al, 1996). In the current study, mirror neurons would be activated upon the observation of the reaching action, resulting in a simulation of the reaching action complete with any performance information such as reach speed, direction etc. Previous research into the effect of action restriction on action observation found a significant effect of restriction on the ability to correctly judge the target object of a reach which could suggest that current physical capability is incorporated in the simulations of other people's actions. The aim of the current experiment is to investigate whether restricting participants' reaching ability significantly influences their ability to process the action information contained within the observed action. If this is indeed the case, we would expect to see significant differences between the responses in the restricted and unrestricted conditions, with responses in the unrestricted conditions representative of the differing speeds of reach but not in the restricted conditions. If this effect is found, then it can be concluded not only that the current availability of actions is incorporated into the performance of mental simulations of the actions of others but also that the ability to understand the actions of others is influenced by the ability to currently perform that action.

This thesis, and the experiments conducted as part of it, present a new and unique insight to the processes employed when performing cognitive tasks involving simulation and bring into question the extent of the contribution the body plays when performing these tasks. It also further questions the importance of the Embodied Cognition perspective (Barsalou, 2003) and suggests alternative explanations in light of the results displayed in this thesis.

Chapter 2-Exploring the relationship between Action availability and Affordance detection

Introduction

Research into the relationship between motor ability and mental simulation has typically focused on tasks which require conscious motor imagery in order to complete, such as mental rotations (Hartman, Falconer & Mast, 2011). Many mental simulations occur automatically on an unconscious level; however these simulations are vastly under-represented in simulation research. The first series of experiments conducted for this thesis focuses on the effect of motor ability on simulations when they are performed at a subconscious level, namely through the observation of objects.

Gibson (1979) proposed that all objects within ones environment communicate "affordances" to the individual. These affordances refer to suggestions of potential interactions that can be performed with these objects, determined and constrained by the sensory-motor abilities of the observer and the environment in which they are viewed. Research has shown that when we observe an object, the actions associated with that object are automatically activated resulting in the covert and unconscious performance, or simulation, of the associated actions, which in turn leads to facilitated performance of that action when it is subsequently performed (Gallese et al, 1996). This series of experiments aims to establish whether temporarily manipulating our physical capabilities had a direct impact on our ability to detect object affordances, in particular the physical aspects of objects that are compatible with the actions being manipulated.

Research suggests that our body schema is heavily involved in the simulation of actions and is constantly updated according to our current physical capabilities in order to aid the accurate planning and performance of actions (Parsons, 1994). When we are physically incapable of performing an action, be it permanently or temporarily, the body schema will represent this incapability resulting in a modification of any future actions in order to take this into account (De'Sperati & Stucchi, 1997). The same processes are used for both the simulation and execution of actions, therefore any simulations that subsequently occur, either on a conscious or subconscious level, should incorporate this incapability into them resulting in a disruption to the simulation.

Previous research into this area has found that restricting movements has a significant effect on our ability to integrate information gained through observing other peoples actions with motor information communicated from the object itself. Ambrosini et al (2011) found that when restrained, participants were significantly impaired at determining the target object of a prehensile movement performed by another individual, even when grasp size information was included in the reach through the forming of an appropriate hand shape. Ambrosini et al (2011) proposed that restricting a compatible movement prevented the participants from being able to accurately simulate the observed action as the motor responses required to do so are temporarily unavailable, resulting in the inability to integrate the visual and motor information presented in the scene. This current series of studies aimed to investigate whether restriction has a similar effect on our ability to make affordance based judgements of objects. Research into simulation and motor resonance would suggest that in order to make any type of functional or structural judgement on an object, the mental representation is accessed and any motor actions that are associated with that object should be activated, resulting in the simulation of appropriate movements (Gallese et al, 1996). Based on the findings of Ambrosini et al's (2011) study, we should expect to see significant differences in response times in restricted conditions compared to unrestricted conditions as restriction should disturb any subsequent simulation of interactions, which in turn should disrupt the ability to determine the handedness of the target objects.

Previous experiments studying the effect of restriction on perception have typically twisted and tied participants' hands behind their backs as a method of restriction (Ambrosini et al, 2011). Research suggests, however, that this form of restriction can disrupt the body schema in more ways than just manipulating the availability of actions. The body schema updates the current positioning of the body through the use of visual, proprioceptive and tactile information. Twisting and tying hands behind the back results in multiple types of tactile stimulation, specifically stimulation of the hands as they meet and stimulation of the arms and mid to lower back, where the arms and back meet during the twisting. In these types of restriction, the body schema is updated quickly due to the extreme change in body position and the high level of sensory, visual and proprioceptive information generated through self-touch (Maravita, Spence & Driver, 2003). As a result, any effect of restriction may be the result of the change in body posture rather than action prevention, and therefore may be more representative of the time it takes to mentally move the hands from the current position to the one more suited to interaction with the object. This series of experiments aimed to determine whether the same effects of restriction could be found when methods of restriction were employed that restricted movement but did not drastically change body posture. The restriction method used in this study consisted of straps attached to the desk directly in front of participant. Participants' hands were placed palm side down and were strapped at both the wrist and hand locations in order to prevent any arm, wrist or hand movement. This is to determine whether preventing an action being performed is sufficient to disrupt the simulation of action, rather than changes in body posture. When participants were unrestricted, their hands remained in the same position but were unrestrained in order to ensure that there was no change in posture that may influence results.

Affordance research has demonstrated that the preparation of a motor action facilitates the detection of object components compatible with that action through the simulation process, resulting in faster responses to objects compatible with the prepared response (Ellis and Tucker, 2001). The aim of this series of studies is to determine whether the reverse is also true, i.e. the prevention of performance of certain actions disrupts the ability to detect object components compatible with that action. If Gibson's (1978) theory that our ability to detect object affordances is constrained by our physical capabilities is correct, we should expect to see significant differences in response times in restricted conditions compared to unrestricted conditions, as restraining the actions compatible with interaction with an object's most salient feature should result in the affordance information becoming less salient through disruption of the simulation process.

2.1 Experiment 1a: Handedness judgements of household objects during action restriction

2.1.1 Introduction

The aim of the first series of experiments was to determine whether restriction of hand movements inhibits affordance detection when participants are required to make explicit affordance judgements of objects. Research suggests that in order to make a handedness judgement of the stimuli participants will access the mental representation of the object which includes information regarding both the visual features of the object and any motor actions associated with it (Gallese et al, 1996). Once this information has been accessed the motor codes associated with that object will be activated, resulting in a simulation of the action most associated with that object and an increased readiness to perform that action. This increased readiness will then facilitate subsequent detection of object components compatible with that action (Symes et al, 2008). If bodily restrictions are represented by the body schema as previously suggested, restricting actions associated with the object component being judged should be reflected in the simulation process, resulting in a disruption to both the simulation and the readiness to perform that action. As a knock on effect, the relevant object information will become less salient which will result in slower judgements regarding that information. Previous research into the area of object affordances has typically focused on the motor activations that occur with observation of the object and the subsequent facilitated detection of those affordances but none to date have examined temporary physical factors that may negatively impact on our ability to detect object affordances. The first experiment in this thesis will therefore look at the effect of action restriction on explicit affordance judgements in an effort to broaden the understanding of the physical mechanisms that are involved in affordance detection.

In this study, participants were presented with black and white images of household tools with a discernible handle and were required to make a left or right finger response according to whether the object was compatible with a left or right handed grasp. Participants were also presented with images of vegetables and were required to withhold responses on these trials, thereby only responding when the stimuli was a household tool. This ensured that participants processed and categorised the objects as being tools rather than responding due to visual cues. Based on previous research, it is predicted that observation of these objects should result in the increased activation of the neural areas associated with that action which in turn should result in potentiation of a specific grasping movement. This potentiation should result in the facilitation of subsequent hand responses, making responses faster in these conditions. When the hands are restricted, this facilitation should be removed as the action is no longer able to be performed, therefore we should see a significant difference between restricted and non- restricted responses when hand responses are made.

The aim of this study was to determine whether prevention of movements compatible with the object component being classified disrupts our ability to detect the object's affordances. Participants performed half of the experiment with their hands and wrists strapped down to prevent any movement. If our ability to access object affordances is directly related to our physical capabilities, as Gibson (1978) would suggest, it is predicted that responses in the restricted condition should be significantly longer than in the unrestricted condition, with significantly more errors made in the restricted condition. If it isn't dependent upon our current physical capabilities, however, then there will be no significant difference in reaction times in the restricted and non-restricted conditions.

2.1.2 Method

Participants

A total of thirty Psychology undergraduates from Plymouth University participated in this study as part of a course requirement for a compulsory module in Research Methods. It was specified at the recruitment stage that participants must have normal or corrected vision as they were required to view visual stimuli as part of the experiment. It was also requested at recruitment that participants must have full mobility in their arms and back, with no history of any chronic pain, strokes or immobility conditions. This was due to previous research which suggests that physical conditions such as these can influence the ability to perform motor simulation tasks (Fiorio, Tinazzi & Aglioti, 2006).

Materials

Stimuli

The stimuli consisted of black and white real life photographs of 10 common tools and 3 vegetables. The images were developed using Adobe® Photoshop® and each image fit into an area of 28cm x 10cm with a black background of 1024 x 768 pixels. All tools had a discernible handle and were household objects that are easily recognised. The objects used were: chisel (x2), hammer, garden fork, knife, mallet, meat tenderizer, potato masher, screwdriver and trowel, carrot, leek, and banana. The tools selected were chosen due to their recognisability and are commonly used in tool use studies (Tucker & Ellis, 2004). The images were presented in the centre of the screen along the horizontal plane and were presented equally in a left handed and right handed grasp orientation. An example of the stimuli used is shown in Figure 2.1.

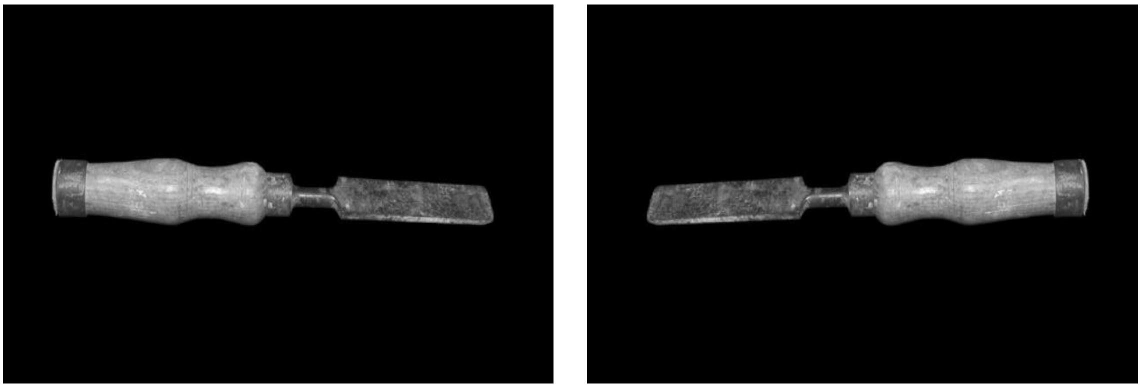


Figure 2.1: *Examples of the tool stimuli in Experiment 1 in a (l) left handed and (r) right handed orientation*

The experiment was developed using the Slide Generator 2007.3.3 program developed by Dr Mike Tucker of the University of Plymouth. It was performed on a Samsung Sync Master 2043 computer screen, with a screen resolution of 1680 x 1050 with 32bt colour quality. Responses were made using keyboard button presses, with a front-slash key indicating a left handed object and a back-slash key indicating a right handed object. These response keys were chosen as they enabled responses to be made with very minimal movement. Responses were standardized across participants, with left hand responses indicating a left handed handle object and right handed responses indicating a right handed handle object.

Restriction

Participants performed half of the experiment with their hands restricted with Velcro straps to prevent them from being able to move their wrists and hands either horizontally or vertically. Participants' hands were placed underneath the straps palms facing downwards and securely restrained enough to prevent movement. Before beginning the experiment, participants were asked to demonstrate required to demonstrate that they could not move their arms, wrists or hands. As the study was investigating the effect of restriction on affordance detection, the order of restriction was balanced between participants, with half performing the first portion of the experiment under restriction and half performing it freely. This was to ensure that restriction order did not influence the results.

Design and Procedure

A within subjects design was used in which each participant was exposed to all conditions. Participants were informed prior to the experiment in both the brief and verbally that some restriction techniques would take place and were shown images replicating the restriction methods employed. Those in the restricted condition then had their hands secured under the restraints and were required to demonstrate that they could not move. The experimenter was present at all times during the procedure to ensure that the participants remained within the restraints as well as for safety reasons.

Each participant was required to perform 5 practice trials with the option of repeating this phase prior to the test trials. Successful completion of the practice phase was required before the experiment could begin. The stimuli images were presented individually on the screen and participants were required to respond as quickly as possible according to whether the object was compatible with a left or right handed grasp, with a left index finger response for left handed tools and a right index finger response for right handed tools. Participants were required to withhold responses on catch trials, i.e. when the stimuli presented was a vegetable. There were two conditions in this experiment: Restriction type (restricted or not restricted) and Response/ handle location (right or left). Object handle location was randomised between slides.

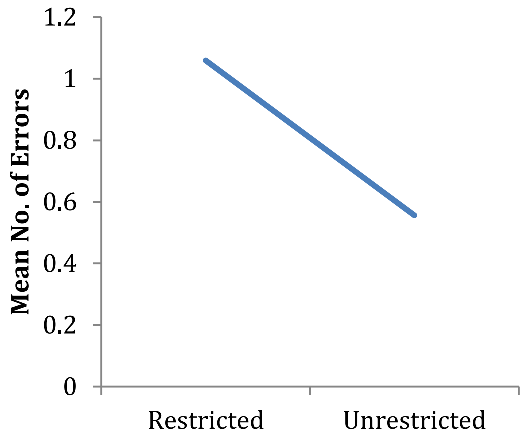
Each trial began with the appearance of a black screen for 500ms to indicate that the trial was about to begin. The stimuli were then presented. Each trial ended when a participant responded or 2000ms had elapsed. The stimuli remained visible until this occurred. A black screen was then displayed for 500ms before the beginning of the next trial. The sequence of stimuli presentation was randomised for each participant.

2.1.3 Results

Error responses and reaction times more than 2SDs from the participant's condition means were excluded from the analysis (total of 0.74% of responses removed from the analysis). All participants were included in the analysis as error rates did not exceed 10%. The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted (R) or unrestricted (UR)) and Response/handle location (left or right).

Main effects

There were no significant main effects of Restriction, F(1,29)= 1.104, p=0.302, $\eta_p^2 = 0.037$ (**R- M=**583.608ms, **SD=**152.34/ **UR- M=**572.143, **SD=**139.5, Figure 2.2) or Response/ handle location, F(1,29)=0.514, p=0.479, η_p^2= 0.017 on reaction times to the stimuli.



(L) Figure 2.2: *Mean reaction times for Restricted and Unrestricted conditions*

(R) Figure 2.3: *Mean number of errors for Restricted and Unrestricted conditions*

Interactions

There was no significant interaction between Restriction and Response/Handle location, $F(1,29)=0.419$, $p=0.523$, $\eta_p^2=0.523$.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean absolute number error score data with within-participant factors of Restriction (restricted or not restricted) and Response/handle location (left or right). The results found no main effects of Restriction, $F(1,29)=0.645$, $p=0.428$, $\eta_p^2= 0.022$, (**R- M=**1.05, **SD=**3.40, **UR- M=**0.556, **SD=**1.00, Figure 2.3) and Response/handle location, $F(1,29)=0.355$, $p=0.556$, $\eta_p^2= 0.012$ on error rates. There was no significant interaction between Restriction and Response/Handle location, $F(1,29)=0.113$, $p=0.739$, $\eta_p^2=0.004$.

Catch trial analysis

Catch trials were removed from the initial analysis. An independent samples t-test was conducted to compare response times towards catch trials in restricted and unrestricted conditions. There was no significant difference between response times during restricted conditions (**M=**57.403, **SD=**197.311) and unrestricted condition (**M=**80.15, **SD=**263.915), t(598)= -1.196, p=0.232.

2.1.4 Discussion

The aim of this study was to investigate whether restricting the ability to perform certain motor actions disrupts performance at detecting object affordances compatible with those actions by disturbing the simulation process. In this study, participants were required to respond according to the handedness of a common household tool whilst their hands and arms were restrained to prevent performance of a grasping movement. In order to make an accurate judgement, previous research suggests that individuals will access mental representations of the object, which will include visual, motor and sensory information gained through previous interactions, and simulate previous interactions in order to accurately determine whether the object is compatible with a left or right handed response(Barsalou, 2003). The results showed that there was no significant effect of restriction on reaction times and no significant interaction between Restriction and Object handle location, which suggests in this case that restricting a compatible movement does not significantly affect our ability to access mental representations and consequentially determine the handedness of objects.

Analysis of the error data demonstrated no significant effect of restriction on the number of incorrect responses made. It was predicted that more errors would be made in the restricted condition due to a disruption in the access of the mental representation of the objects. The results indicate that restricting compatible motor actions did not have a significant effect on handedness judgements, which indicates that restriction did not disrupt either access to the mental representation or subsequent simulation of the actions.

Hand responses were used in this experiment as it was predicted that observation of the tool should result in activation of the motor areas associate with interaction with that object, facilitating performance of subsequent hand responses. As a result of this, hand responses should be most susceptible to the effect of restriction (Craighero & Zorzi, 2012); however the results suggest that restriction has no significant effect on RT using hand responses. A possible explanation for the lack of significant effect of restriction on response times in this study could be the result of hand movements being made as responses, signifying to the body schema that movement is available in this motor area and therefore potentially compromising the restriction technique. In order to investigate whether this is the case, Experiment 1 was replicated with voice responses made instead of a limb response, in order to determine whether the temporary restriction of a compatible movement is sufficient to disrupt the simulation of movements when no physical movement is required as a response

2.2 Experiment 1b- Handedness judgements of household objects during action restriction using voice response

2.2.1 Introduction

The main aim of Experiment 1b was to determine whether the lack of significant main effect of restriction demonstrated in the first experiment was due to the use of finger responses. In the previous experiment, participants viewed objects that afforded either a left or right hand action and responded with their fingers with their hands restrained; thereby potentially signalling to the body schema that action was possible. To address this issue, the next study used verbal responses instead of finger responses, in order to investigate whether affordance information is less salient to the individual when the actions required to interact with that affordance are unavailable for performance and a non-limb response is required. Based on previous research, it was predicted that when participants were restricted, the body schema and subsequent simulated actions should represent the action restriction, thereby making the affordance less salient as the corresponding action is unable to be performed. It was again therefore predicted that responses in the restricted condition should be significantly slower and less accurate than when the movement is available for action.

2.2.2 Method

Participants

A total of thirty participants took part in this study. Plymouth University students participated as part of a course requirement for a compulsory module in Research Methods. Paid participants were also recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. Again, it was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms and back, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. It was also specified at recruitment that participants must speak English as their first language, to prevent any language effects.

Materials

The same stimuli set were used from the previous experiment. Verbal responses were used in this experiment; therefore responses were recorded using a voice response device developed by Herga Electric Limited, which was connected to a parallel port. The box has an inbuilt microphone and responses were recorded from the onset of the word. The voice box recorded when the response had been made, however actual responses were recorded manually. The responses were standardised across participants, with a "left" verbal response for a left handed grasped object and a "right" verbal response for a right handed grasped object.

Restriction

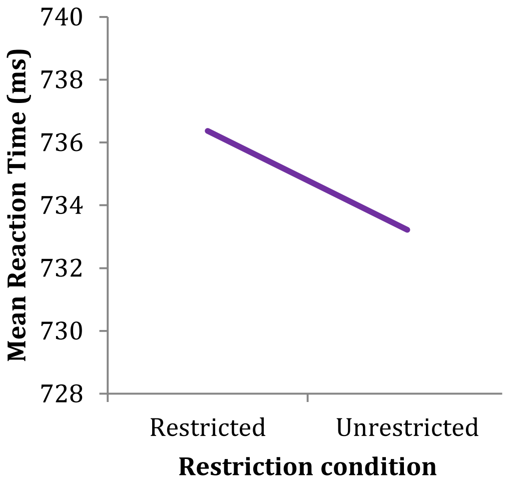
The same restriction methods were used from the previous experiment.

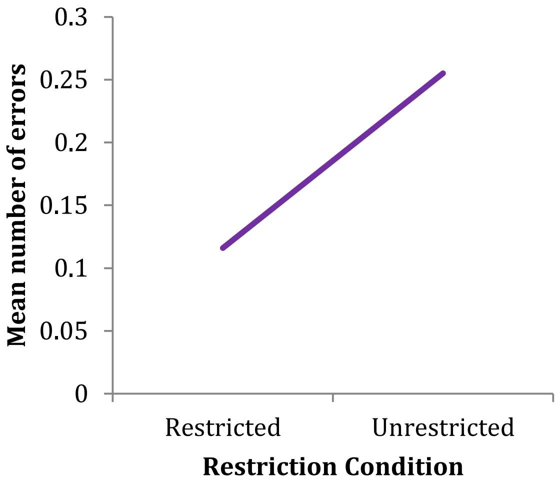
Design and Procedure

The design and procedure is identical to that in Experiment 1a, however responses were made verbally.

2.2.3 Results

Error responses and reaction times more than 2SDs from the participant's condition means were excluded from the analysis (0.17% of responses we removed from the analysis). All participants were included in the analysis as error rates did not exceed 10%. The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted or not restricted) and Response/handle location (left or right).





(L) Figure 2.4: *Mean reaction times for Restricted and Unrestricted conditions*

***(R)* Figure 2.5:** *Mean number of errors for Restricted and Unrestricted conditions*

Main Effects

There is no main significant main effects of Restriction, F (1, 29) =0.113, p=0.739, η_p^2 =0.004 (**R- M=**736.42ms, **SD=**201.30/ **UR- M=**733.39, **SD=**201.95, Figure 2.4) or Response/Handle location, F (1.29) =1.740, p=0.197, η_p^2 = 0.057 on reaction times to the stimuli.

Interactions

There is no significant interaction between Restriction and Response/Handle location, F(1,29)=0.039, p=0.844, η_p^2 =0.001.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean error score data with within-participant factors of Restriction (restricted or not restricted) and Response/handle location (left or right). The results found no main effects of Restriction, F(1,29)=2.351, p=0.136, η_p^2 = 0.075 (**R- M=**0.116, **SD=**0-.46/ **UR- M=**0.255, **SD=**0.59, Figure 2.5) and Response/handle location, F(1,29)=0.000, p=1.,

η_p^2 = 0.000 There was no significant interaction between Restriction and Response/Handle location, F(1,29)=0.326, p=0.573, η_p^2 = 0.011.

Catch trial analysis

Catch trials were removed from the initial analysis. An independent samples t-test was conducted to compare response times towards catch trials in restricted and unrestricted conditions. There was no significant difference between response times during restricted conditions (**M=**23.7633, **SD=**118.007) and unrestricted condition (**M=**28.60, **SD=**120.305), t (598)=-0.497, p=0.619.

2.2.4 Discussion

The aim of this study was to investigate whether restricting motor capability affects our ability to process object affordances compatible with those actions, in this case the effect of restriction of hand movement on our ability to detect the handedness of objects. Voice responses were used in this experiment to determine whether temporary restriction of a compatible movement is sufficient to disrupt the simulation of movements when no physical movement is required for a response.

The results of this study demonstrated that there was no significant main effect of Restriction on affordance judgements of the stimuli even when no overt physical movement is required for response, which again suggests that the restriction of corresponding motor actions does not prevent or disrupt our ability to detect components of the object related to the action being restricted. There was also no significant effect of Handle position on responses, with no significant difference between response times made towards left and right handed objects. The results also indicated that there was no significant difference in the amount of errors made in the restricted and unrestricted conditions.

2.2.5 General Discussion

The results of both experiments in this set indicate that the immediate ability to perform an action is not a requirement for accurate affordance judgements. In this study, participants were required to respond according to the handedness of tools communicated by the position of their handle, whilst withholding responses when presented with an image of a vegetable or fruit. As a consequence of this, participants should access mental representations of the stimuli before any response can be made in order to determine whether the object is a tool or a fruit. These mental representations will not only contain information about the visual properties of the object but will also provide information regarding previous motor and sensory activations. Activation of these motor properties should then lead to the mental simulation of those actions which should facilitate the performance of those actions when they are subsequently performed (Gallese et al, 1996). It was predicted that restricting the motor actions associated with the object feature the participants were making judgements on would disrupt the simulation process, thereby inhibiting the retrieval of affordance based information which is characterised by increased response times in the restricted conditions. However, the findings of this study suggest that this is not the case and that when the action is not available, affordance information can still be accessed with the same speed and accuracy.

It was predicted in this study that the restriction of actions compatible with interaction with the objects should be reflected in the body schema, which will in turn be incorporated into any subsequent simulations that occur. The motor simulations that are taking place in this study are performed on a very unconscious level through the observation of manipulatable objects; therefore it is possible that these simulations are not influenced by changes to the body schema in the same way as conscious simulations. This proposition would therefore imply that different processes are involved in performance of simulations which are determined by the type of simulations that are occurring. This will be discussed in more detail in the Discussion.

In this study, participants were required to make very explicit judgements regarding the handedness of a common household object. It was predicted that in order to do this, interactions with the object would be simulated in order to determine the accurate response hand. However, it is possible that the lack of restriction effects found in this study may be the result of visual techniques being used to make the judgements rather than motor based processes. Participants were required to respond when a tool was presented and withhold responses when a vegetable was presented. All of the objects used in this study were of a similar shape so that participants would be forced to categorise them as tools before a response could be made. It is possible, however, that participants did not access previous interactions with the object to make their response but rather based it on the visual properties of the object. The task required participants to respond according to which hand was compatible with interaction with the object, however rather than accessing previous interactions with the object to make their response, participants would have been able to accurately respond based on the abstract positioning of the handle. For example, objects with their handle positioned to the left are compatible with a left handed grasp but the same response can be made purely through the processing of the visual positioning of the object handle. This level of processing would not necessarily require activation of the motor areas associated with the object and as a consequence of this, motor simulations may not actually occur in this study. If this is indeed the case, then it is possible for action information regarding an object to be accessed without activation of the appropriate motor areas, however further investigation would need to be made regarding this before a firm conclusion can be made. This will be discussed further in the Discussion chapter.

The previous experiments focused on the effect of action restriction on handedness judgements of household tools, where the handle was an active part of the study which participants were required to actively categorise in order to accurately respond. It was predicted that restricting actions would disrupt the simulation of actions thereby disturbing the accessibility of affordance information; however the results suggest that restriction did not significantly affect the ability to gather affordance based information from the object and make explicit affordance judgements. It is possible that the judgements required in this study could have been performed using visual rather than motor techniques and therefore would not be influenced by action restriction. As a result of this finding, the next set of experiments in this chapter will investigate whether restriction can influence the simulation of actions in tasks where robust affordance based effects are found without the need for explicit affordance based judgements using the Temporal Order Judgement paradigm and the Stimulus-response compatibility effect. The presence of strong object affordance effects in these paradigms suggests that motor simulations are taking place on a very unconscious level, therefore if the availability of actions influences affordance detection through the disturbance of motor simulations we should expect to see a significant effect of restriction in these paradigms. If there is no significant effect of restriction on affordance detection in the following studies we can therefore conclude that the ability to perform a compatible action is not a prerequisite for affordance detection.

2.3 Experiment 2: Temporal Order Judgements (TOJ) of household objects

2.3.1 Introduction

The second experiment in this chapter aims to investigate whether the physical availability of actions has a significant effect on affordance detection when the objects themselves are not critical to the experiment. In the previous study, participants were required to make explicit affordance judgements of stimuli and the results indicated that there was no significant effect of restriction on these judgements. In Experiment 1 judgements regarding object affordances were critical to successful completion of the task, however research has shown that object affordance effects can be so potent that they influence responses even when the object itself is not critical to the task. These strong affordance effects indicate that motor simulations are occurring; therefore if action availability is required for accurate affordance detection we should see an effect of action restriction in these tasks. The second experiment in this chapter investigated the effect of restricting compatible movements on affordance detection using the Temporal Order Judgement paradigm.

The following study is based on research carried out by Roberts and Humphreys (2010) looking at the effect of action partnerships between object pairs on the active-object bias found during temporal order judgements. In their study the object pairs consisted of one "active" object, which is distinguished as the object that is physically manipulated, such as a wine bottle, and one "passive" object which is typically held steady throughout interaction, such as a wine glass. In their study, participants were presented with images of an active object and a passive object that were either action compatible with each other, for example a paintbrush and a paint pot, or action incompatible with each other, for example a paintbrush and a wine glass, and were required to judge which object was presented first or second. These objects were presented with varying stimulus onset asynchronies (SOAs) and were either presented in a position that indicated that the objects were interacting functionally with each other, with the active object positioned facing towards the passive object, or not, with the active object facing away from the passive object. Previous research into object TOJs has shown that when objects are positioned correctly for action, the active object is perceived to appear before the passive object (Roberts and Humphreys, 2010). An explanation for this perceptual bias can be found in affordance research. As previously explained, the perception of a graspable object results in the automatic activation of the response codes associated with interaction with that object, leading to enhanced attention processing and facilitated performance of compatible responses when required to act (Tucker & Ellis, 1998). This occurs due to the mental simulation of performance of the appropriate responses. When objects are positioned correctly for interaction, not only between themselves but individually, the Visuo-motor neurons associated with the action implied by the two objects together will be activated, leading to enhanced processing of the active object as it is that object which will more strongly afford a physical action over the passive object. This enhanced processing leads to the active object being perceived to appear first as that object that will literally "grab" the individual's attention (Roberts and Humphreys, 2010). When the objects aren't positioned correctly for interaction the objects do not form a functional unit therefore the action associations that exist between the two objects are removed, resulting in a dissipation of the attention bias towards the active object.

Roberts and Humphries (2010) found that the active object bias was also dependent on the order judgement that participants made. When participants were required to make a first object judgement, the active object bias found between interacting objects was not present, however when required to make a second object judgement the active object bias was present. An explanation for this is that participants need to process both objects in order to make a judgement as to which came second, therefore responses towards objects presented correctly for interaction in these trials are more susceptible to the active object bias, as the affordances communicated by the active object in the functionally interactive pair will be more salient to the individual. When the participants make judgements regarding which object appeared first only the first object needs to be processed, therefore the functional interaction between the pair will not necessarily be processed and consequently the active object will not bias attention in trials when the passive object is presented first.

Support for the active object bias theory can be found in mirror neuron research. In a study by Tipper, Paul and Hayes (2006), participants were presented with images of door handles positioned to the left or right either in a depressed state to represent that it had been acted upon (active) or in a non-depressed state to represent inactivity (passive) and were required to respond according to either the colour or shape of the handle using their right or left hand. Tipper et al (2006) predicted that the objects presented in the active state will provoke larger affordance/response compatibility effects as these objects imply that an action has been performed upon it by another individual and, according to mirror neuron research, should result in the same neuron activity when the participants process the handle as if they performed the action themselves (di Pellegrino, Fadiga, Fogassi, Gallese & Rizzolatti, 1992). The results of this study found significant affordance/response compatibility effects when the handle was presented in an active state compared to passive orientations, with faster response times towards active objects than passive objects when the responding hand was compatible with interaction with the object. The results of both this and Roberts and Humphries' (2010) study support the theory that the attention bias towards active objects when positioned ready for action is due to the Visuo-motor priming effects that are communicated by the active object in the pair, resulting in enhanced processing of that object over the passive object which is characterised by the perception that the active object appears before the passive object.

In the current study, participants were presented with images of two active and passive household objects and were required to judge the temporal order of the objects, i.e. which came first or second. These pairs consisted of items that are commonly paired with each other, such as a bowl and spoon, and items that are not commonly paired together, for example a bowl and screwdriver. Based on previous research, the active object bias should still occur in uncommon pairings when the objects are presented interacting functionally with each other and therefore have been included in the current study. The objects were either positioned correctly for interaction, for example a wine bottle angled towards a wine glass as if it were pouring wine, or incorrectly, in this example with the neck of the wine bottle facing in the opposite direction to the glass. Based on previous research, it is predicted that the restriction of actions compatible with interaction with the active object will result in a disruption to both the simulation of actions that occurs upon the processing of an object and the subsequent access of affordance information of the active object, resulting in a removal of the attention bias towards active objects in restricted trials when the objects are presented interacting with each other. In order to investigate whether manipulating ability to perform an action influences our ability to perceive object affordances, participants in the current experiment performed half of the experiment with their hands restricted.

In this experiment, the order of object presentation was randomised, with half of trials featuring a passive object first and half featuring an active object first in order to investigate the effect of restriction on these trials. Based on previous research, it is expected that there will be significantly more active object first judgements in the active object first trials and significantly more passive object first judgements in the passive object first trials as they do indeed appear first. We are therefore not predicting that participants will perceive significantly more active objects appearing first in the passive object first conditions. However, if restricting actions does disturb affordance information retrieval through disturbance of motor simulations, we would expect to see a significant difference in the number of active object first judgements made in the two restricted conditions in the passive and active object first trials separately. As a consequence of this, the passive object first and active object first trials will be analysed separately as well as collectively to see if restriction has separate effects on these trials.

In typical TOJ experiments, the point of subjective simultaneity (PSS) is calculated to determine the point at which the two objects are judged to appear simultaneously. In this study, however, the sum of trials in which active objects are judged to appear first is of most interest as this will demonstrate whether the basic active object bias is occurring on a general level. If restricting performance of compatible actions disturbs our ability to access affordance information, we would expect to see no significant difference in functionally interacting trials between the number of trials in which participants perceive the active object to appear first and the passive object to appear first in restricted conditions. If this is indeed the case, then it can be concluded that the ability to process object affordances is directly linked to our ability to perform a compatible action.

2.3.2 Method

Participants

A total of thirty two Psychology undergraduates from Plymouth University participated in this study as part of a course requirement for a compulsory module in Research Methods. It was specified at the recruitment stage that all participants must have normal to corrected vision due to the fact that they were required to view visual stimuli as part of the experiment. It was also requested at recruitment that participants must have full mobility in their arms, with no history of any chronic pain, strokes or immobility conditions such as arthritis.

Materials

Stimuli

The stimuli consisted of greyscale images of six active objects (hammer, wine bottle, jug, key, screwdriver, spoon) and six compatible passive objects (nail, wine glass, glass, padlock, screw, bowl) (Rossion & Pourtois, 2004). The experimental scenes consisted of one active object and one passive object consistently presented in a downwards alignment, with the active object at the top of the screen and the passive object in the bottom opposite corner in order to mimic real life interactions. Each object was paired with both its compatible object and a non-compatible object from the opposite set (bottle and padlock; hammer and bowl; jug and screw; key and wine glass; screwdriver and glass; spoon and nail) and was presented correctly or

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Figure 2.6: *Examples of stimuli-(l) Padlock and key positioned correctly for interaction and (r) incorrectly for action*

incorrectly for interaction. The objects were presented equally in left and right handed orientations. See Figure 2.6 for an example trial scene.

The experiment was developed using the Slide Generator 2007.3.3 program developed by Dr Mike Tucker of Plymouth University. It was performed on a Samsung Sync Master 2043 computer screen, with a screen resolution of 1680 x 1050 with 32bt colour quality. The responses in this study were made using foot response devices developed by Herga Electric Limited connected to a parallel port. Foot pedals were located on the floor 300mm apart to mimic a comfortable foot position.

Restriction

The same restriction techniques were used as in previous experiments. As the study was investigating the effect of restriction on affordance detection, the order of restriction was balanced between participants, with half performing the first portion of the experiment under restriction and half performing it freely. This was to ensure that restriction order did not influence the results. There was therefore a gap of approximately 5 minutes between the restriction blocks to enable both preparation and release of restriction.

Design and Procedure

A within subjects design was used in which each participant was exposed to all conditions. Participants were informed prior to the experiment in both the brief and verbally that some restriction techniques would take place and were shown images replicating the restriction methods employed. Those in the restricted condition then had their hands secured under the restraints and were required to demonstrate that they could not move. The experimenter was present at all times during the procedure both to ensure that the participants remained within the restraints and for safety reasons.

Each participant was required to perform 5 practice trials with the option of repeating this phase prior to the test trials. Successful completion of the practice phase was required before the experiment could begin. In each trial, one object was presented prior to the other, with active objects preceding passive objects at timings of 50ms, 33.3ms, 16.6ms, -16.6ms, -33.3ms, -50ms (minus numbers indicating that the passive object was presented first). These timings were used in order to prevent any expectancy effects from the participants; however they are not included in the analysis. 16 participants were required to respond according to which object they perceived to appear first and 16 participants were required to respond according to which object they perceived to appear second, with a left foot response if it was the object on the left side of the screen and a right foot responses if it was the object on the right side of the screen. There were 3 within-participant conditions in this experiment: Restriction type (restricted or not restricted), Presentation (correct or incorrect) and Pairing (compatible or incompatible), with a between-participant's factor of Response Order (first object or second object). Restriction condition was blocked but all other within-participant conditions were randomised between slides.

Each trial began with the appearance of a black screen for 500ms to indicate that the trial was about to begin. The stimuli were then presented which was followed by the presentation of a black scene, during which participants were required to respond. Each trial ended when a participant responded or 5000ms had elapsed. A black screen was then displayed for 500ms before the beginning of the next trial. The sequence of stimuli presentation was randomised for each participant.

2.3.3 Results

Reaction times more than 2SDs from the participant's condition means were excluded from the analysis (total 0.7% responses removed from the analysis). All participants were included in the analysis as non-response rates did not exceed 10%. Trials in which active objects appeared first and passive objects appeared first were analysed separately, as well as collectively in order to investigate whether restriction has differing effects on active object first judgements in the two different trial types. The sum of active first judgements was calculated and the mean for each condition was computed for each participant. An Analysis of Variance (ANOVA) was performed on the condition means with within-participant factors of Restriction type (restricted or not restricted); Pairing (correct/incorrect) and Presentation (correct/incorrect) with a between-participant factor of Response order (first object/second object) (see Appendix 1 for full analysis).

Figure 2.7: *Mean Active object first judgements for Passive object first trials by Restriction condition*

Passive objects appear first

Main effects

There was a significant main effect of Presentation on responses, F(1,30)=18.86, p=<0.0001, η_p^2 =0.386, with significantly more active object judgements when the objects were correctly positioned for action (M= 12.094) compared to when objects were incorrectly positioned for action (M=10.211). There were no significant main effects of Restriction, F(1,30)=1.397, p=0.246, η_p^2 = 0.045, (**R**- M=11.492ms, **SD=**152.34/ **UR**- M=10.813, **SD=**139.57, Figure 2.7), Pairing, F(1,30)=0.992, p= 0.327, η_p^2 =0.032 and Response order, F(1,30)=2.905, p=0.099, η_p^2 =0.099 on active object first judgements.

Interactions

There was a significant interaction between Pairing and Response order, F(1,30)=5.313, p=0.028, η_p^2 = 0.150, with significantly more active object first judgements towards incorrect pairs when participants judged what came first compared to more active judgements when towards correctly paired objects when

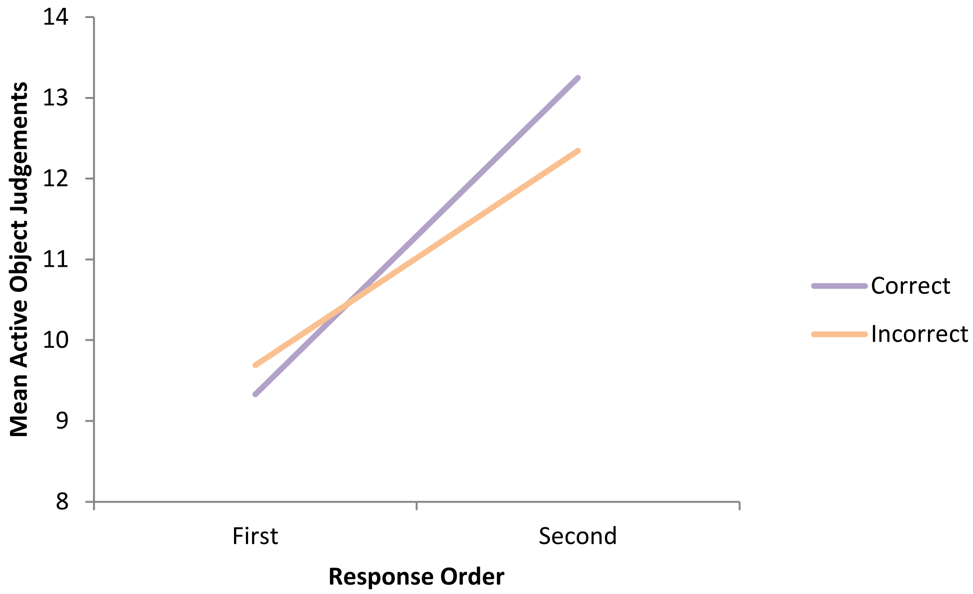


Figure 2.8: *Mean Active object first judgements for Passive object first trials by Response Order and Pairing*

participants judged which object came second (Figure 2.8). There were no significant interactions between Restriction and Response order, F(1,30)=1.737, p=0.198, η_p^2 = 0.055, Presentation and Response order, F(1,30)=2.689, p=0.111, η_p^2 = 0.082, Restriction and Pairing, F(1,30)1.559, p=0.221, η_p^2 =0.049, Restriction and Presentation, F(1,30)=1.868, p=0.182, η_p^2 =0.059, or Pairing and Presentation, F(1,30)=0.357, p=0.555, η_p^2 =0.012. There we no significant three way interactions between Restriction, Pairing and Response order, F(1,30)=0.523, p=0.475, η_p^2 =0.017, Restriction, Presentaion and Response order, F(1,30)=2.046, p=0.163, η_p^2 =0.064, Pairing, Response and Presentation, F(1,30)=0.082, p=0.777, η_p^2 =0.003, or Restriction, Pairing and Presentation, F(1,30)= 0.736, p=0.398, η_p^2 =0.024, or four way interaction between Restriction, Pairing, Presentation, and Response order, F(1,30)=0.479, p=0.494, η_p^2 =0.016.

Discussion:

Passive object first trials only were included in this analysis in order to investigate whether action restriction significantly affected the number of active first judgements when active objects never appear first. Any active first judgements that are made can be concluded as being the result of the active object bias. The results of this analysis show no significant effect of restriction on the number of active object first judgements and no significant interactions between restriction and any of the other factors, which suggests that restricting compatible movements does not interfere with the motor simulation believed to contribute to the active object bias.

The significant main effect of Presentation is in the direction found in previous object TOJ studies (Roberts and Humphries, 2010), with significantly more active first judgements when the objects are positioned accurately for interaction compared to when positioned incorrectly. However, there was no significant interaction between Response order and Presentation as found in previous experiments. This suggests that there was no significant difference in active object first judgement numbers towards correctly or incorrectly positioned objects when participants responded according to which object appeared first or second. It was predicted that as participants would be required to process both objects in order to make a judgement as to which came second, responses in these trials towards objects presented correctly for interaction should be more susceptible to the active object bias, as the object affordances communicated by the active object in the pair will be more salient to the individual. However, the lack of significant interaction, combined with the lack of main effect of Response order, suggests that response order does not significantly influence the saliency of affordance information communicated by the objects, resulting in a lack of active object bias in these conditions. This is in contrast to the results found in the original study (Roberts and Humphries, 2010), which suggests that even when making a judgement on which object appears first, individuals automatically process both object in the scene resulting in activation of the appropriate motor codes of both objects. This therefore brings into question the robustness of the findings in the original study.

There was no significant main effect of Pairing in these trials, with no significant difference between active first judgements towards objects that are paired correctly for interaction or incorrectly paired. This finding is in line with previous research, which has shown that the familiarity of the object pairs does not significantly affect the temporal order judgements (Roberts and Humphries, 2010). The results did, however, demonstrate a significant interaction between Pairing and Response order, with significantly more active first object judgements towards incorrectly paired objects when participants judged which came first and more active first object judgements towards correctly paired objects when participants judged which object came second. This finding suggests that when participants need to process both objects in order to respond, as occurs in the second object judgements, the pairing of the objects significantly effects judgements resulting in an increased active object bias towards correctly paired objects. This suggests that active object affordances are more salient when there exists a recognised functional relationship between the objects. Support for this can be found in simulation research, which suggests that the observation of objects triggers access to the mental representation of that object. This representation includes motor information not only about the object itself but also includes information about objects that are experienced alongside that object (Barsalou, 2008). As a consequence of this, the observation of a pair of familiar objects will lead to the activation of motor responses compatible with these objects, with an increased motor activation as a result of the active object as it is this object that is most strongly associated with motor actions. This then results in an active object bias in these pairs over unfamiliar pairs. However the lack of significant main effect of pairing and interaction between pairing and presentation on judgements suggests that it is only when both objects need to be processed that this relationship significantly influences active object first judgements.

The results of this analysis suggest that even when a passive object exclusively appears first, active objects were still perceived to appear first in some trials and this bias was significantly influenced by whether the two objects were presented as functionally interacting with each other. However active object first judgements were not significantly influenced by whether the physical actions associated with interaction with the active object were available for performance.

Active objects appear first

Main effects

There was a significant main effect of Presentation on response orders, F(1,30)=7.436, p=0.011, η_p^2 = 1.199, with significantly more active object judgements when the objects were correctly positioned for action (M=24.008) compared to objects that were incorrectly positioned for action (M=23). There was no significant main effects of Restriction, F(1,30) =0.213, p=0.648, η_p^2 =0.007, (**R- M=**23.62, **SD=**5.24/ **UR- M=**23.39, **SD=**5.57, Figure 2.9) Pairing, F(2.260)=2.260, p=0.143, η_p^2 =0.070, and Response order, F(1,30)=0.00, p=0.996, η_p^2 = 0.00 on active object judgements.

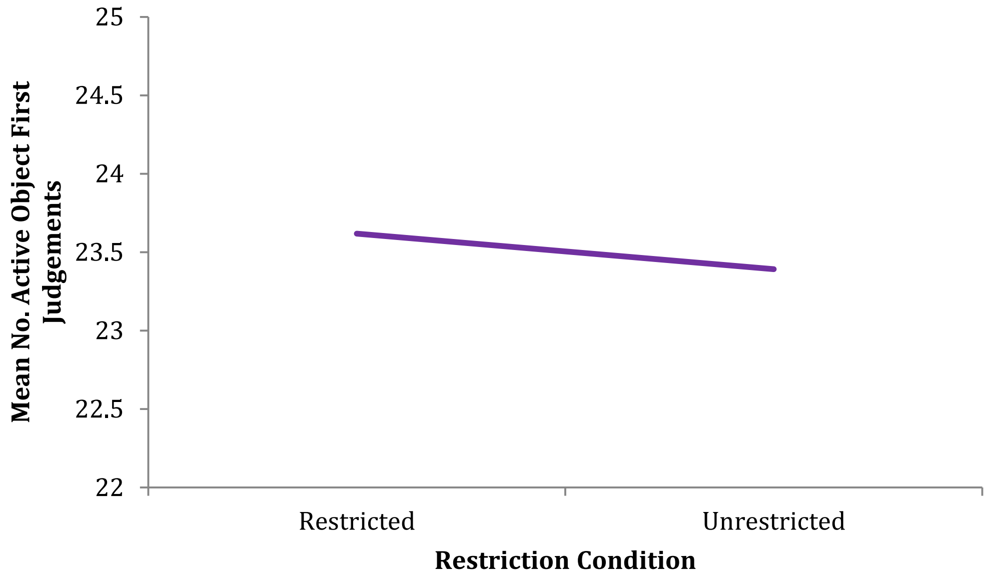


Figure 2.9: *Mean Active object first judgements for Active object first trials by Restriction condition*

Interactions

There was a significant interaction between Presentation and Response order, F(30,1) =5.706, p=0.023, η_p^2 = 0.160 (Figure 2.10). There were no significant interactions between Restriction and Response order, F(1,30)=0.468, p=0.499, η_p^2 = 0.015, Pairing and Response order, F(1,30)=0.000, p=0.985, η_p^2 = 0.00, Restriction and Pairing, F(1,30)=0.449, p=0.485, η_p^2 =0.016, Restriction and Presentation, F(1,30)=6.14, p=0.439, η_p^2 =0.020, or Pairing and Presentation, F(1,30)=0.014, p=0.908, η_p^2 =0.000. There were no significant three way interactions between Restriction, Pairing and Response order, F(1,30)=0.188, p=0.668, η_p^2 =0.006, Restriction, Presentation and Response order, F(1,30)=1.558, p=0.222, η_p^2 =0.049, Pairing, Response and Presentation, F(1,30)= 0.044, p=0.835, η_p^2 =0.001, Restriction, Pairing and Presentation, F(1,30)=0.102, p=0.751, η_p^2= 0.003 or four way interaction

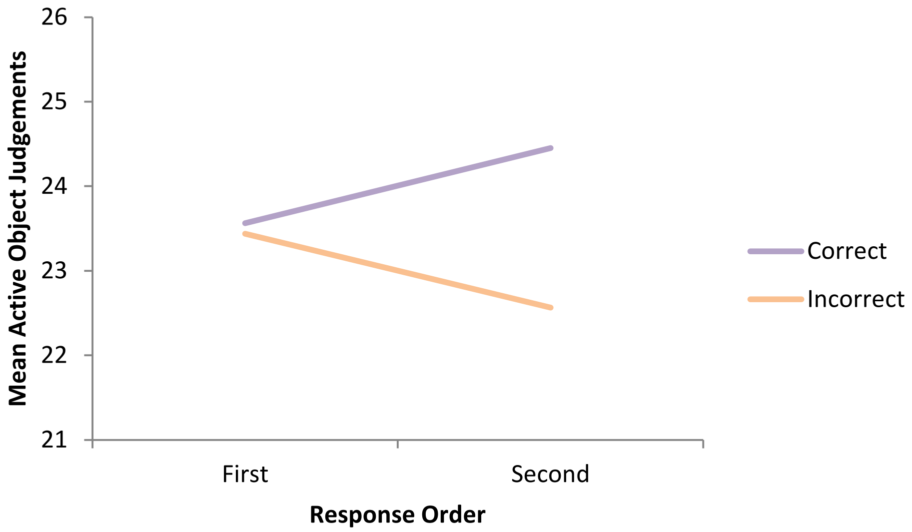


Figure 2.10: *Mean Active object first judgements for Active object first trials by Response Order and Presentation*

between Restriction, Pairing, Presentation, and Response order, $F(1,30)=3.290$, $p=0.80$, $\eta_p^2=0.099$.

Discussion

Again, the results of this study indicate that restricting the actions associated with interaction with the active object does not significantly affect the number of active first judgements and the lack of significant interaction between restriction and the other conditions suggests that restricting the ability to physically interact with the active object does not disrupt the action simulation process that is predicted to contribute to the active object bias

The results of this analysis again indicated a significant main effect of Presentation on results, with significantly more active object judgements when the objects were positioned correctly for interaction compared to when they were positioned incorrectly. This suggests that even when the active object exclusively appeared first, the presentation of the two objects in the scene significantly influenced the perceived temporal order of the objects. The results of this analysis also demonstrated a significant interaction between Object Presentation and Response order, with similar numbers of active object judgements between correctly and incorrectly presented objects when responding to which object came first, but a greater difference in judgements towards those stimuli when judging which came second, with a greater number of active first judgements when the objects were correctly positioned compared to when incorrectly positioned. The results of this analysis suggest that the active object bias is not significantly influenced by whether or not the objects are positioned interacting with each other when only one object needs to be processed to make a judgement, as occurs in the first object judgements. However, when both objects are processed, as occurs in the second object judgements, the active object bias is significantly affected by the positioning of the objects. This can be explained by the increased motor resonance effect created by the active object when presented in a functioning unit, resulting in an active object bias when the two objects are processed as functionally interacting with each other, as occurs when making a second object judgement.

Active and passive combined

Main effects

There was a significant main effect of First object on Active object judgements, with significantly more active first judgements when the Active object was presented first (M=23) compared to when the passive object was presented first (M= 11), $F(1,30)$= 56.269, $p<0.0001$. η_p^2 = 0.652. There was also a significant main effect of Presentation on active object first judgements, with significantly more active first judgements when objects are correctly presented (M=18.051) compared to when incorrectly presented (M=16.605), $F(1,30)$= 16.330, $p<0.0001$. η_p^2 = 0.352.

Figure 2.11: *Mean Active object first judgements by Restriction condition*

The between participants factor of Response order was also significant, with significantly greater active object first judgements when judging which object comes second (M=18.152) than when judging which object comes first (M=16.504), F(1,30)=4.446, p=0.043, η_p^2 = 0.129. There was no significant main effects of Restriction, F(1,30)=1.614, p=0.214, η_p^2 *=0.054* (**R- M=**17.55**=, SD=**8,43/ **UR-M=**17.10, **SD=**8.53, Figure 2.11) or Pairing, F(1, 30)=2.692, p=0.111, η_p^2 =0.082 on active object first judgements.

Interactions

There was a significant interaction between object Presentation and Response order, F(1,30)= 4.964, p=0.034, η_p^2 = 0.142 (Figure 2.12). There was also a significant interaction between First object and object Presentation, F(1,30)= 5.571,p=0.025, η_p^2 =0.157 (Figure 2.13). There were no significant interactions between Restriction and Response order, F(1,30)=0.350, p=0.0559, η_p^2 =0.012,

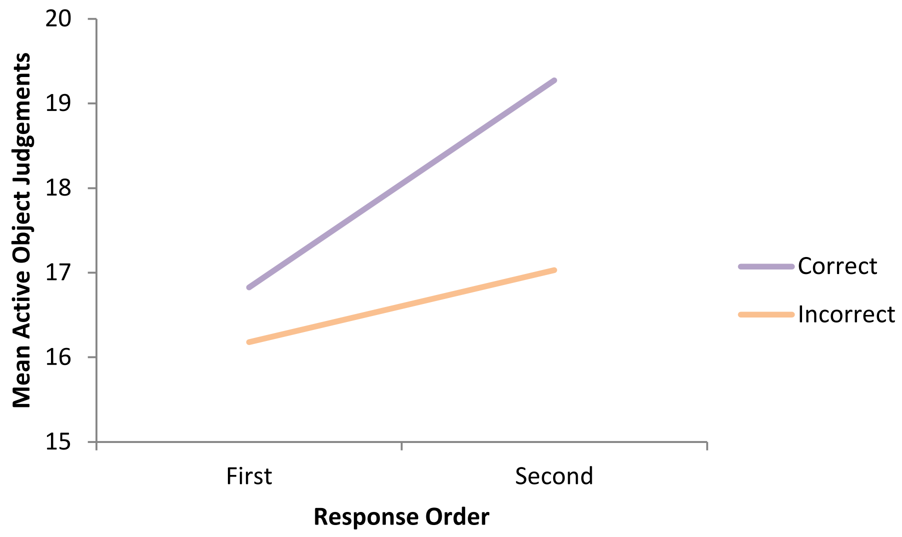


Figure 2.12: *Mean Active object first judgements for Experiment 2 by Response Order and Presentation*

First object and Response order, F(1,30)0.993, p=0.327, η_p^2 = 0.032, Pairing and Response order, F(1,30)1.443, p=0.239, η_p^2 = 0.046, Restriction and First object, F(1,30)=0.323, p=0.574, η_p^2 = 0.011, Restriction and Pairing, F(1,30)=2.022, p=0.165, η_p^2 = 0.063, First object and Pairing, F(1,30)=0.577, p=0.453, η_p^2 = 0.019, Restriction and Presentation, F(1,30)=2.554, p=0.121, η_p^2 = 0.078, First object and Presentation, F(1,30)=5.571, p=0.025, η_p^2 = 0.157, or Pairing and Presentation, F(1,30)=0.078, p=0.782, η_p^2 = 0.003 There were no significant three-way interactions between Restriction, First object and Response order, F(1,30)= 1.884, p=0.180, η_p^2 =0.059, Restriction, Pairing and Response order, F(1,30)= 0.051, p=0.823, η_p^2 = 0.002, First object, Pairing and Response order, F(1,30)=2.093, p=0.158, η_p^2 =0.065, Restriction, First object and Pairing, F(1,30)=0.161, p=0.691, η_p^2 =0.005, Restriction, Presentation and Response order, F(1,30)=4.036, p=0.054, η_p^2 =0.119, First object, Presentation and Response order, F(1,30)=0.215, p=0.646, η_p^2 =0.007, Restriction,

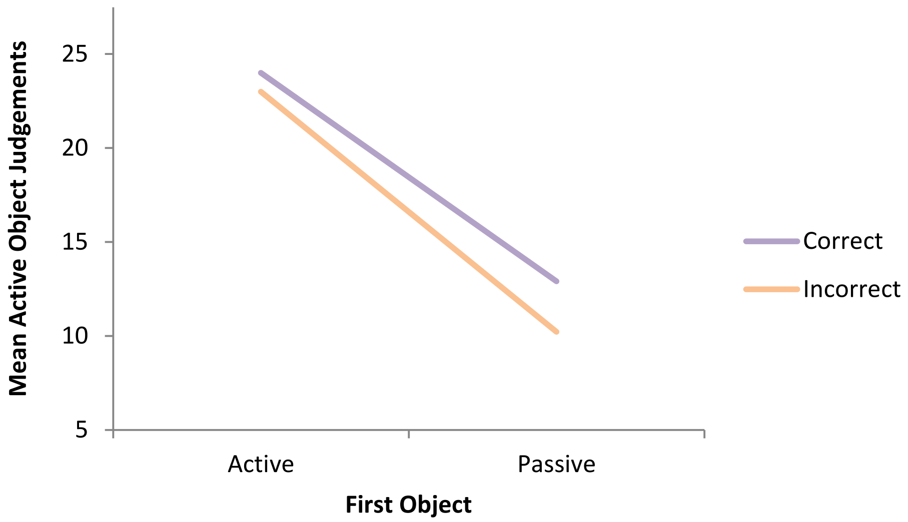


Figure 2.13: *Mean Active object first judgements for Experiment 2 by First Object and Presentation*

First object and Presentation, F(1,30)=0.105, p=0.748, η_p^2 = 0.003, Pairing, Presentation and Response order, F(1,30)=0.098, p=0.758, η_p^2 = 0.003, Restriction, Pairing and Presentation, F(1,30)=0.167, p=0.685, η_p^2 = 0.006, or First object, Pairing and Presentation, F(1,30)=0.314, p=0.579, η_p^2 = 0.010, no significant four way interactions between Restriction, First object, Pairing and Response order, F(1,30)=0.646, p=0.428, η_p^2 = 0.021, Restriction, First object, Presentation and Response order, F(1,30)=0.002, p=0.968, η_p^2 = 0.000, Restriction, Pairing, Presentation and Response order, F(1,30)=1.998, p=0.168, η_p^2 = 0.062, First object, Pairing, Presentation and Response order, F(1,30)=0.002, p=0.968, η_p^2 = 000, or Restriction, First object, Pairing and Presentation, F(1,30)=1.232, p=0.276, η_p^2 =0.039 and no significant 5 way interaction between Restriction, First object, pairing, Presentation and Response order, F(1,30)=0.520,p=0.476, η_p^2 = 0.017.

Discussion

The results of this analysis again demonstrate that restriction had no significant effect on any active object bias that occurs during this study. This suggests not only that restricting actions compatible with interaction with the active object does not significantly influence the temporal order judgements of the stimuli but that restricting actions does not interfere with the processing of affordance information, as demonstrated by the lack of significant main effect of restriction on judgements.

The results demonstrated a main effect of First object on responses, with significantly more active first judgements when active objects were presented first compared to when passive objects were presented first. This finding is as expected but what is interesting is not the number of judgements made when the active object appeared first, as we would expect to see a higher number of active object judgements made in these trials, rather it is the number of active first judgements made when the passive object was first presented. The results in these trials indicated that passive objects were perceived to appear first in more than 2/3rds of responses, with active objects only judged to appear first in less than 1/3rd of trials. These results bring into question whether an active object bias indeed exists in this experiment or whether it is indeed too subtle an effect to be shown in this type of analysis.

Again, there was a significant main effect of Presentation on responses, with significantly greater active first responses when the objects were pictured interacting correctly with each other, however there was no effect of the familiarity of the object pairs on these judgements. This finding suggests that regardless of whether the two objects are traditionally paired with each other, the interaction presentation of these two objects significantly affects active object judgements. This finding is in line with previous research and suggests that when two objects are perceived as interacting as a functioning pair, the increased motor resonance communicated by the active object results in a mental simulation of the action associated with it, drawing the participant's attention to that object which leads to the perception that it appears first. The results also supported previous research by demonstrating a significant main effect of response order on active object judgements, with significantly more active first judgements when judging which object appears second compared to first object judgements.

The results also indicated a near significant interaction between Restriction, Presentation and Response order, with greater Active object first judgements when judging which object came second when objects were presented correctly for action and a very slight increase when participants were restricted. This finding, although not significant, is in the opposite direction to what was predicted, as it was predicted that restriction of actions would result in the removal of the active object bias in this conditions. This effect, however, is most likely due to the highly significant interaction between Presentation and Response order and as there is no interaction between Restriction and the two other variables independently, we can conclude that this is most likely not a true interaction

2.3.4 General Discussion

The aim of this study was to investigate whether restricting the ability to perform an action significantly influences the active object bias usually demonstrated in object based TOJ experiments by disrupting participants' ability to process object affordances. In this study, participants were required to respond according the temporal order of two objects presented at varying times from each other, whilst their hands and arms were restrained to prevent performance of a movement compatible with interaction with the object. The hypothesis of this experiment was that restraining the movements associated with interaction with the active object would disrupt the simulation process that occurs upon the processing of that object and as it is this process that is ultimately held responsible for the active object bias in these situations, should result in the removal of the active object bias in temporal order judgements. The results of this study indicated no significant difference between the numbers of active object first judgements made when participants were restrained compared to when unrestrained and no significant interactions between restriction and the other conditions, which suggests that manipulating individuals ability to perform an action compatible movement does not interfere with temporal order judgement of object stimuli.

Previous research into temporal order judgements of objects has found an active object bias in participants' temporal judgements when objects are positioned correctly for action, with participants judging the active object to appear first significantly more often than passive objects. This bias is attributed to the motor activations and consequent motor simulation that occurs as a result of observing the two objects interacting functionally with each other, with increased motor activations from the active object as it is this object that typically requires physical manipulation. This increased motor activation towards the active object results in a focusing of attention to this object, which results in the illusion that the active object appears before the passive object. The result of all 3 analyses demonstrate a significant main effect of presentation on active first judgements, with significantly more active first judgements when objects were positioned correctly for action compared to when the objects were positioned incorrectly, regardless of the familiarity of the object pairs. This finding is in line with previous research in this area; however it is difficult to determine from the results whether this effect is the result of the correct positioning of the objects as a pair or the correct positioning of the active object for action. It is possible that the main effect of presentation found in all analyses is the result of the correct positioning of the active object over the passive object. In all trials, the active object was positioned in the top of the screen and the passive object in the bottom. In the incorrectly positioned trials, the active object was directed away from the active object; however the positioning of the passive object remained consistent throughout. It is therefore possible that the active bias found in the correctly presented trials is actually a result of the presentation of the active object alone, rather than the functional relationship between the two objects. Roberts and Humphries (2010) conducted a limited analysis on the results of their study between the compatibility between participants' handedness and the relative ease of use of the active objects and found no bias for active objects positioned comfortably for interaction according to handedness. However this analysis should be treated with caution as it was conducted on a limited sample and therefore further research needs to be conducted in this area before firm conclusions can be made.

This series of studies focused on the effect of restriction on the unconscious simulation of actions through the motor resonance effect. In this study, participants responded to the temporal order of the presented objects and the results found that when objects were presented correctly for interaction, active objects were judged as appearing first significantly more than passive objects; however this effect was not mediated by the restriction conditions. The findings of this study suggest that when the objects themselves are processed, affordance effects result in a bias towards the active object as it is that object that is typically associated with physical interactions. The final set of experiments in this chapter will build on this finding and will investigate the effect of restriction on affordance detection when an abstract feature of the object is critical to the task but the object itself is not using the Stimulus-Response compatibility effect paradigm.

2.4 Experiment 3a: Object based Stimulus-Response Compatibility effect

2.4.1 Introduction

Research into motor facilitation, in particular the Stimulus-Response compatibility effect, has shown that even when the object itself is not a critical part of the study, handle position can directly influence RTs with faster RTs when the responding hand is compatible with the position of the handle (Tucker & Ellis, 2001). This finding demonstrates that the observation of an object, even when interaction is not possible, automatically potentiates the appropriate response needed, facilitating subsequent performance of this action. This is known as the orientation effect (Tucker & Ellis, 1998). The aim of this next experiment is to determine whether restriction of actions compatible with interaction with an object will disrupt the orientation effect using the object based Simon effect paradigm. This paradigm is being used as previous research using this paradigm has demonstrated very potent affordance based effects on responses, which indicates that even when the objects themselves are not critical to the task, motor simulation and motor resonance occurs which interferes with the responses stipulated by the task (Tucker & Ellis, 2001). As a consequence of this, if action availability is crucial for action simulation and accurate affordance detection, restriction effects should be evident in this paradigm.

In this study, participants were presented with a 3D image of a red or green mug centrally presented with its handle positioned to the left or right and were required to respond according to its colour with either a right or left handed response. Results of studies using this paradigm have demonstrated significant effects of handle/affordance location on responses, with facilitated responses when the responding hand is compatible with the affordance most saliently communicated by the object and a disruption in responses when the two response locations are not compatible (Tucker & Ellis, 2001). This effect is explained by the existence of simultaneously occurring response codes communicated by the locations of the stimuli and response. In congruent trials (i.e. those where the response and affordance location are compatible) the two responses activated are compatible and therefore no competition occurs, resulting in facilitated responses. In trials where the response and stimuli location conflict with each other, competition between the responses activated will occur which needs to be resolved before the correct response can be made, resulting in an increased reaction times and error rates (Rubichi, Iani, Nicoletti & Umilta, 1997). In this study, participants will be required to respond with either a left or right hand response according to the colour of the object which will have a handle either positioned to the left or right. Based on motor resonance research, observation of the mug should automatically result in activation of the appropriate actions required to interact with the object through action simulation, in this case a left or right handed grasp, resulting in facilitated responses when this action is subsequently performed (Murata, et al, 1997). When this action is compatible with the response determined by the task, in this example a right or left handed responses, responses will be facilitated. When the action afforded by the object conflicts with that determined by the task competition between the two responses will occur, resulting in delayed responses, as the conflict needs to be resolved before an accurate response can be made, and increased errors as a result of the strength of the affordance and lack of inhibition of the incorrect response.

Previous research into the use of objects in the SRC task has demonstrated a very strong stimulus-response compatibility effect which typically shows that responses are facilitated when the response compatible for interaction with the most salient affordance of the object is the same as that required for response (Tucker & Ellis, 2001). It is therefore predicted that an affordance effect will be found in this study, with facilitated responses when the hand required for action is the same as that required for interaction with the object. The direction of the handle was manipulated instead of stimuli location in order to determine whether restriction of compatible actions results in the removal of the stimulus-response compatibility effect through disruption to the simulation of actions required to respond with the object. In this study, the objects were presented centrally, with equal amounts of the mug appearing on both sides of the screen; therefore there was no attention bias as a result of the positioning of the handle. If only the Simon effect is present, where responses are facilitated due to an attention bias rather than an affordance based bias, we should expect to see facilitated responses when the responding hand is on the opposite side of the handle, as the main body of the mug covers a larger area and therefore should evoke an attention bias and a subsequent location/response compatibility effect. If an SRC affordance effect occurs, however, then we should expect to see facilitated responses when the responding hand corresponds with the direction of the object handle and disrupted responses when the two responses conflict, as participants are processing the affordance communicated by the position of the handle.

If a relationship exists between the ability to perform an action and affordance retrieval, restricting movements compatible with the action component of an object, in this case the handle, should disrupt the ability to process affordance information making it less likely to conflict with the actions required by the task. If this is the case, it is predicted that in the restricted condition, the retrieval of affordance information communicated by the object should be disrupted therefore diminishing the stimulus-response compatibility effect, resulting in increased response times in these trials and no significant difference between the RTs in trials where the response and stimuli location are compatible and in those where they are not. However, in non-restricted conditions, responses will be facilitated when the direction of the handle is compatible with the response location, as in the traditional stimulus response compatibility effect task. Based on previous object based SRC research, it is also predicted that more errors will be made in conflicting trials in the unrestricted condition compared to the restricted condition, as disruption of the Stimulus-response compatibility effect should also disrupt the conflict between the response location and stimuli location resulting in greater levels of accuracy in restricted conditions.

2.4.2 Method

Participants

A total of thirty participants took part in this study. Paid participants were recruited from the Plymouth University Psychology School of Psychology paid participant pool and took part in this study for payment of £4. It was specified at the recruitment stage that all participants must have normal to corrected vision and must not suffer from colour blindness, due to the fact that the participants will be required to respond according to the colour of the stimuli for the experiment. It was also requested at recruitment that participants must have full mobility in their arms and back, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia.

Materials

Stimuli

The stimuli used for this study were 2D computer created images of a mug coloured red or green with a handle positioned either to the left hand side or to the right. Examples of the stimuli used are shown in Figure 2.7. The images were developed using Adobe® Photoshop® and measured 405 x 455 pixels from the top of the mug to the bottom and from the side to the far edge of the mug handle. The stimuli were presented centrally at a consistent height in the middle of the screen (525 pixels) and were presented on a black background. Equal numbers of coloured stimuli and handle positions were used in this study. Only one stimuli was present in each trial.

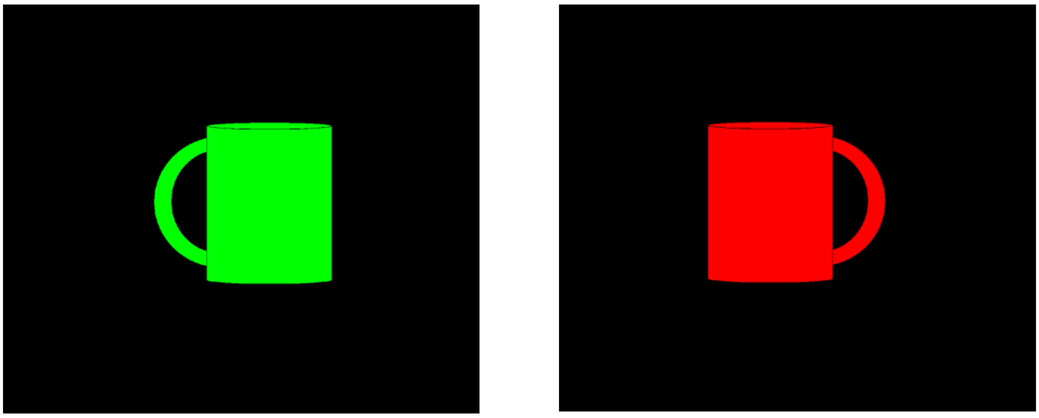


Figure 2.14: *Examples of stimuli-(l) Green mug with handle positioned to the left and (r) Red mug with handle positioned to the right*

The experiment was developed using the Slide Generator 2007.3.3 program developed by Dr Mike Tucker of the University of Plymouth. It was performed on a Samsung Sync Master 2043 computer screen, with a screen resolution of 1680 x 1050 with 32bt colour quality. Responses were made using keyboard button presses, with a front-slash key indicating a left handed object and a back-slash key indicating a right handed object. These response keys were chosen as they enabled responses to be made with very minimal movement. Responses were balanced across participants, with half responding with their left hand to a red object and half responding with their right hand to red objects, with opposite hand allocations for the green objects. Participants were randomly assigned to the response conditions.

Restriction

The same restriction methods were used as in the previous experiments.

Design and procedure

A within subjects design was used in which each participant was exposed to all conditions. Participants were informed prior to the experiment that some restriction techniques would take place and were shown images replicating the restriction methods employed. Those in the restricted condition then had their hands secured under the restraints and were required to demonstrate that they could not move. The experimenter was present at all times during the procedure to ensure that the participants remained within the restraints and for safety reasons.

Each participant was required to perform 5 practice trials with the option of repeating this phase prior to the test trials. Successful completion of the practice phase was required before the experiment could begin. The stimuli images were presented individually on the screen and participants were required to respond as quickly as possible according to the colour of the object, with a left hand response for a red object and a right hand response for green object in response set 1 and vice versa for response set 2. There were 3 conditions in this experiment: Restriction type (restricted or not restricted), Object handle position (left and right), and Response (right or left). Object location and object colour was randomised between slides.

Each trial began with the appearance of a black screen for 500ms to indicate that the trial was about to begin. A fixation cross appeared in the middle of a black screen preceding the presentation of each stimulus and remained visible for 250ms. The stimuli were then presented. Each trial ended when a participant responded or 2000ms had elapsed. The stimuli remained visible until this occurred. A black screen was then displayed for 500ms before the beginning of the next trial. The sequence of stimuli presentation was randomised for each participant.

2.4.3 Results

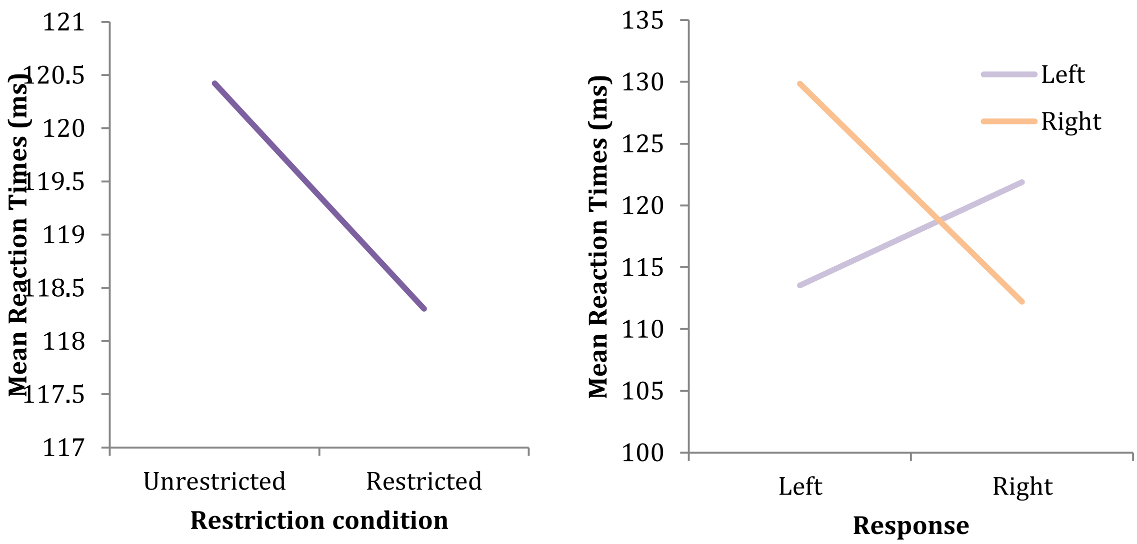
Error responses and reaction times more than 2SDs from the participant's condition means were excluded from the analysis (total 2.38% of responses removed from the analysis). All participants were included in the analysis as error rates did not exceed 10%. The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted or not restricted), Response hand (left or right) and Handle Position (left and right) (See Appendix 1 for full analysis).

Main Effects

There was no significant main effect of Restriction, F(1,29)=0.113, p=0.739, η_p^2 = 0.004, (**R- M=**118.304ms, **SD=**439.82/ **UR- M=**120.422, **SD=**433, Figure 2.15)Response, F(1,29)=1.468, p=0.235, η_p^2 =0.048 or Handle Position, F(1,29)=0.624, p=0.436, η_p^2 = 0.021, on reaction times to the stimuli.

Interactions

There was a significant interaction between Response hand and Handle Position, F(1,29)=6.332, p=0.018, η_p^2 = 0.018, with significantly shorter RTs when the Handle Position and Response hand are congruent (Figure 2.16).



(L) Figure 2.15: *Mean Response times (in ms) for Restriction conditions*

(R) Figure 2.16: *Mean Response times (in ms) for Experiment 3a by Response and Handle Position.*

for details. There were no significant interactions between Restriction and Response hand, $F(1,29)=0.197$, $p=0.661$ $\eta_p^2 = 0.007$, or Restriction and Handle Position, $F(1,29)=0.563$, $p=0.459$. $\eta_p^2 = 0.019$. The three-way interaction between Restriction, Response and Handle Position was not significant, $F(1,29)=0.564$, $p=0.459$, $\eta_p^2 = 0.019$.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean error score data with within-participant factors of Restriction (restricted or not restricted), Response (left or right) and Handle Position (left/right). The results found no main effects of Restriction, $F(1,29)=1.012$, $p=0.323$, $\eta_p^2 = 0.034$ (**R- M=**2.475, **SD=**1.08/ **UR- M=**2.150, **SD=**1.07, Figure 2.17), Response, $F(1,29)=0.139$, $p=0.712$, $\eta_p^2 = 0.005$, and Handle Position, $F(1,29)=2.374$, $p=0.134$, $\eta_p^2 = 0.076$ on error rates. There were

Figure 2.17: *Percentage of errors by Restriction Conditions*

no significant interactions between Restriction and Response, F(1,29)=0.355, p=0.556, η_p^2 = 0.012, Restriction and Handle Location, F(1,29)=3.092., p=0.089, η_p^2 =0.096 and Response and Handle Location, F(1,29)=2.840, p=0.103, η_p^2 = 0.089. The three-way interaction between Restriction, Response and Handle Location was not significant, F(1,29)=0.031, p=0.861, η_p^2 =0.001.

2.4.4 Discussion

The aim of this study was to determine whether the restriction of actions removes the stimulus-response compatibility effect by disrupting the saliency of affordance information communicated by the objects when the object is not critical to the response required. The results indicate a significant interaction between response and stimuli location, with significantly faster responses when the response location and the location indicated by the object are congruent, but no significant three way interaction between restriction, response and stimuli location, with no significant difference between the SRC effect when participants were restrained and unrestrained. In this study it was predicted that restricting the actions compatible with the most salient feature of the object, in this case the handle, would disrupt the simulation process and result in that affordance information becoming less salient, therefore disrupting the SRC effect. The presence of a SRC in the restricted trials indicates that even when participants were unable to physically perform a compatible action and the object was not a critical part of the experiment, to the extent that participants need not even process the object itself in order to make the response, the location of the handle was still processed and facilitated congruent responses and competed with incongruent responses. The implications of this will be discussed further in the general discussion.

An interesting finding in this study, however, was the lack of a significant SRC effect in the error results. In a typical SRC effect experiment, participants make more errors in the conditions where the response and object affordance conflict, due to the competing location codes needing resolving before a response can be made ,which increases both the response time and the chance of error. In this study, the error results indicate that there was no significant difference between the number of errors made in congruent and incongruent response conditions, although the results trend in that direction. The error results also show that there was no significant three way interaction between restriction, response and handle location; therefore we cannot attribute the lack of error SRC to the restriction methods involved. One possible explanation for this finding could be an accuracy/time trade off- participants were informed to respond both as quickly and as accurately as possible throughout the study. The significant interaction between Response and Handle location indicates that response times towards incongruent stimuli were significantly larger than responses towards congruent stimuli; therefore it is possible that this increased reaction time towards incongruent stimuli could be increasing the level of accuracy in these conditions. In order to control for this in the next experiment, participants will be instructed to respond as quickly as possible, with no mention of accuracy.

The aim of this study was to determine whether restricting hand movements disturbs individuals' ability to identify object affordances associated with that movement, such as the handedness of objects, by disrupting the simulation process. In this study, participants responded with their fingers according to whether the object was red or green. As a result of this, it may be possible that this action was sufficient to communicate to the body schema that action is available, thereby undermining the restriction process. In order to determine whether the participants ability to move their fingers, even though only marginally, may have compromised the experiment, the study was replicated with foot responses used instead of hand responses, in order to determine whether restriction of the action required to interact with the object disrupts the SRC when another limb is used to make the response.

2.5 Experiment 3b: Object based Stimulus-Response Compatibility effect in Objects- foot response

2.5.1 Introduction

In the previous study, participants responded with their index fingers using a button press; however it is possible that the minimal action was sufficient to disrupt the restriction process by making a hand action still available for use, which could explain the SRC effect found in the restricted condition. In order to investigate whether this is a factor, in this study participants responded with their feet according to the colour of the object whilst their hands were restrained or unrestrained. Research suggests that affordances are transferable between limbs therefore as a consequence of this we should still expect to see an SRC effect when foot responses are made (Craighero & Zorzi, 2012). As predicted in the previous study, if the participants unconsciously process the action related features of the objects when making their response, then we should expect to see a motor resonance/facilitation effect characterised as a significant SRC effect in participants responses, with facilitated responses when the response location is compatible with that communicated by the objects handle and significantly longer response times when the two locations compete. This effect should remain in the unrestricted condition, however when participants are restricted the action relevant information communicated by the object should be less salient and therefore less likely to interfere with the response information determined by the object colour. This should therefore result in no significant difference in the restricted condition between responses when they are compatible with the direction of the handle or not.

2.5.2 Method

Participants

A total of thirty different participants took part in this study. Plymouth University students participated as part of a course requirement for a compulsory module in Research Methods. Paid participants were also recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. Again, it was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms and back, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. Finally, as foot responses were required for the entire experiment, it was specified that participants must have full mobility in their feet and wear appropriate footwear on the day to avoid any performance issues.

Materials

The same stimuli set were used from the previous experiment. Responses were made using foot pedals developed by Herga Electric Limited connected to a parallel port. Foot pedals were located on the floor 300mm apart to mimic a comfortable foot position. Responses were balanced across participants, with half responding with their left foot to a red object and half responding with their right foot to red objects, with opposite foot allocations for the green objects. Participants were randomly assigned to the response conditions.

Restriction

The same restriction methods were used from the previous experiment.

Design and Procedure

The design and procedure is identical to that in Experiment 3a, however responses were made using foot pedals.

2.5.3 Results

Error responses and reaction times more than 2SDs from the participant's condition means were excluded from the analysis (total 2.86% of responses removed from the analysis). All participants were included in the analysis as error rates did not exceed 10%. The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted or not restricted), Response foot (left or right) and Handle Position (left and right).

Main Effects

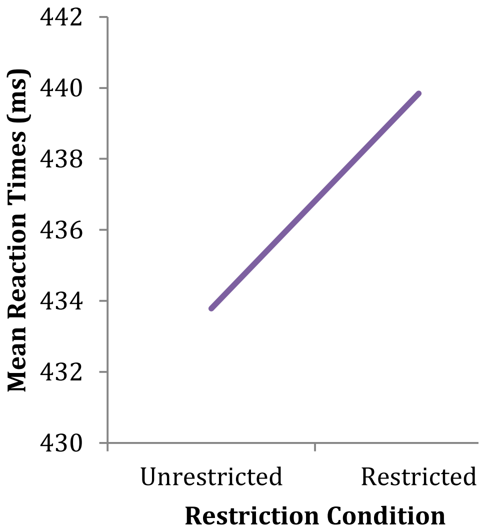
There was no significant main effect of Restriction, F(1,29)=1.881, p=0.181, η_p^2 = 0.061, (**R- M=**444.44ms, **SD=**115.41/ **UR- M=**456.81, **SD=**123.71, Figure 2.18), Response, F(1,29)=1.500, p=0.231, η_p^2 = 0.049, or Handle Position, F(1,29)=0.117, p=0.735, η_p^2 = 0.004 on reaction times.

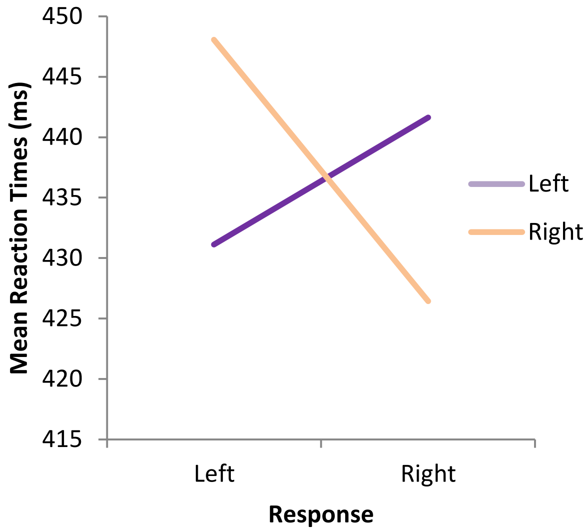
Interactions

There was a significant interaction between Response and Handle Position, F(1,29)=27.004, p<0.0001, η_p^2 = 0.482, with significantly shorter RTs when the stimulus location and responding foot are congruent (Figure 2.19) . There were no significant interactions between Restriction and Response, F(1,29)=1.358, p=0.253, η_p^2 = 0.045 or Restriction and Handle Position, F(1,29)=0.230, p=0.635, η_p^2 = 0.008. The three-way interaction between Restriction, Response and Handle Position was not significant, F(1,29)=2.016, p=0.166, η_p^2 = 0.065.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean error score data with within-participant factors of Restriction (restricted or not restricted), Response (left or right) and Handle Position (left/right). The results found no main effects of





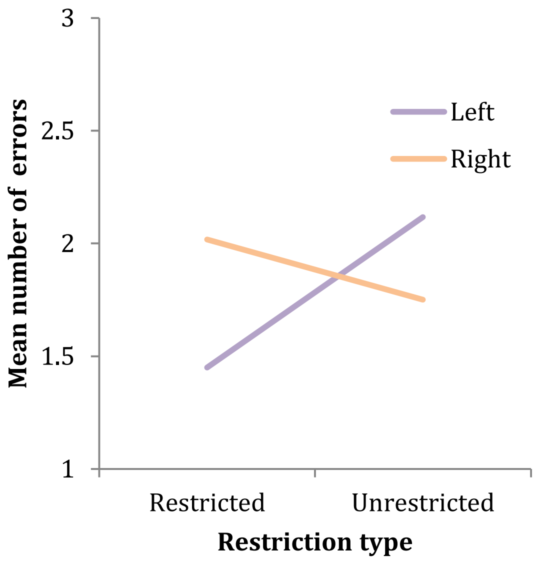
(L) Figure 2.18*: Mean Response times (in ms) by Restriction Condition*

(R) Figure 2.19*: Mean Response times (in ms) for Experiment 3b by Response and Handle Position.*

Restriction, F(1,29)=3.379, p=0.076, η_p^2 = 0.104, (**R- M=**2.750, **SD=**1.94/ UR-**M=**3.050, **SD=**1.97, Figure 2.20), Response, F(1,29)=0.118, p=0.734, η_p^2 =0.004, and Handle Position, F(1,29)=1.216, p=0.279, η_p^2 =0.043 on error rates.

Interactions

There was a significant interaction between Restriction and Response, F(1,29)=5.768, p=0.021, η_p^2 = 0.166, with significantly more errors in the restricted condition when a right foot response was required, and significantly more errors in the unrestricted condition when a left foot response was required (Figure 2.21). There was also a significant interaction between Response and Handle Position, F(1,29)=9.072, p=0.005, η_p^2 = 0.237,with significantly less errors when the response foot was congruent with the Handle location. There was no significant interaction



(L) Figure 2.20: *Mean Error rates by Restriction Condition.*

(R) Figure 2.21: *Mean Error rates for Experiment 3b by Restriction and Response.*

between Restriction and Handle Location, F(1,29)=0.704, p=0.408, η_p^2 =0.025. There was also no significant three-way interaction between Restriction, Response and Handle Location, F(1,29)=0.252, p=0.620, η_p^2 =0.009.

2.5.4 Discussion

The aims of this study was to determine whether the restriction of actions compatible with interaction with the object stimuli removes the stimulus-response compatibility effect by disrupting the motor facilitation effect when foot responses are used. The results again indicate that there was a significant interaction between response and stimuli location, with significantly faster responses when the response location and the location indicated by the object are congruent, but no significant three way interaction between restriction, response and stimuli location, with no significant difference between the SRC effect when participants were restrained and unrestrained. These results indicate that even when hands are completely restrained and responses are made with the feet the restriction does not prevent or disturb the processing of affordance information.

In the previous study, the error analysis found no significant difference in error rates, which was attributed to a potential accuracy-time trade off. In order to control for this, in this study participant were instructed to respond as fast as possible with no mention of accuracy. The error analysis indicates that there was a significant interaction between response location and handle location, with significantly more errors when the handle and response locations conflict compared to when they are compatible, which is in line with previous Simon effect research. The error results also show, however, that there is no significant three way interaction between restriction, response and stimuli location, with no significant difference between the SRC errors made when participants were restrained and unrestrained. It was predicted that when participants were restrained, the affordance information communicated by the object would be less salient as the action compatible with it is not available for performance. This should in turn result in the removal of the SRC effect in error results as there should be no facilitation of responses and therefore no bias of congruent over incongruent stimuli in terms of both response times and error rates. The presence of a SRC in error rates suggests that restraining participants' ability to move their hand does not interfere with their ability to process affordance information as previously predicted.

2.5.5 General Discussion

The presence of a Stimulus-Response compatibility effect in both experiments, with facilitated responses when affordance and response were congruent, and higher error rates in Experiment 3b in incongruent conditions, suggests that even when the object itself was not a critical part of the study, the location of the handle was processed by the participants and the subsequent motor activation interfered with the response process. This is in line with previous SRC affordance research which has shown that even when the object is not a critical part of the study, action information about the object is automatically processed and can interfere or facilitate subsequent action performance (Ellis & Tucker, 2001).

The results of the two studies follow similar patterns, with significant evidence of a stimulus response compatibility effect between the location of the response and the handle position when responses are made using both hands and feet. This finding brings into question the process behind the orientation effect itself. In this study, participants responded to the colour of a centrally placed object with its handle located to either the left or right. As previously mentioned, the body of the mug takes up more area than the handle therefore if the responses are guided by attention rather than affordances we would expect to see a SRC as a result of the direction of the mug body rather than the handle. The presence of an SRC in both experiments in favour of the handle location suggests therefore that responses are guided by the affordances communicated by the object. However the presence of a SRC effect when foot responses are made suggests that there may be more abstract events taking place as the objects themselves do not afford a foot related action. Phillips and Ward (2002) proposed that affordance effects do not necessarily potentiate a specific limb response, rather a more abstract coding that potentiates an action that can be performed using various methods. This abstract coding theory is supported by the TEC which suggests that the motor resonance effect occurs as a result in an overlap between action and perception systems, therefore perception of an object results in the activation of an abstract action response rather than a specific motor response (See Chapter 1 for a review of the TEC- Hommel, et al 2001). The presence of an affordance effect in foot responses suggests that the orientation effect is indeed the result of abstract rather than action specific coding, therefore restriction of a hand movement in this study would not disturb the ability to process the affordance of the object as the object itself does not exclusively potentiate a hand response. This will be discussed further in the Discussion Chapter.

The results of this study indicate that the restriction of compatible actions did not interfere with the SRC effect and that even when the object itself was not critical to the study affordance effects were still capable of influencing motor responses. This suggest that motor simulations were occurring in these studies and that the prevention of actions did not disturb the simulation process sufficiently enough to disrupt affordance detection. In the standard Simon effect experiments, responses are facilitated when the response codes generated by the location of the object and the location of the response required are the same and are inhibited when the response codes compete. In these studies it was predicted that restricting movements compatible with interaction with the salient object component, in this case the handle, should disrupt affordance retrieval resulting in the removal of the SRC effect in restricted conditions. This was due to the prediction that restricting compatible movements results in a disruption to the unconscious simulation of actions that occurs upon viewing an object, making handle position information less salient and therefore not able to interfere with or facilitate responses. The presence of a SRC effect in both restricted and unrestricted conditions suggests that that this did not occur and, more importantly for this thesis, that the ability to perform a movement is not a prerequisite of affordance, or at least object handedness, information retrieval.

It was previously predicted that restricting actions resulted in a disturbance in the simulation of subsequent actions through changing the body schema. The results of the current series of experiments suggest however that this is not the case. In this series, the simulations that were predicted to occur would do so on a very unconscious level, therefore it is possible that these types of simulations are not dependent on current physical capabilities. The next series of experiments therefore aims to investigate this further by looking at the effect of action restriction on responses when conscious motor simulations are required, using the mental rotation paradigm.

Chapter 3- Exploring the relationship between 3D Object Rotations and action availability

Introduction

In the previous series of experiments, participants made affordance based judgments of objects whilst under restraint in order to determine whether restriction of compatible actions disrupted the unconscious simulation of interaction with that object. In these tasks, the simulation of actions is performed unconsciously through the observation of the objects and the results indicated no significant effect of restriction on affordance detection. This series of studies aims to investigate whether restricting actions can have a significant effect on performance of conscious simulations of actions, through the use of mental rotation.

Mental rotation tasks are typically used as an example of motor simulations as research has shown that individuals use robust motor imagery methods in order to perform these rotations that result in the activation of the same motor process as when physically interacting with an object (Parsons, Fox, Downs, Glass, Hirsch, Martin, Jerabek & Lancaster, 1995). In standard mental rotation tasks, such as those by Shepard and Metzler (1971), participants are presented with two abstract 3D images rotated at varying degrees of separation from each other and are required to judge whether they are the same or mirror images. This task is completed by mentally rotating the test image to bring it into line with the other image. When required to physically perform a rotation of an object, the law of physics constrains the movement of the object so that it must move along a continuous trajectory. When mentally performing a rotation, these constraints do not exist therefore it is possible for mental images to undergo a transformation that does not involve rotation along a continuous trajectory (Kosslyn, et al 1998). However, the results of these tasks typically demonstrate that response times increase as the degree of rotation increases along a continuous trajectory, which is in line with performance when physically rotating an object. Kosslyn (1994) suggested that mentally rotated objects follow a trajectory because the individual is mentally simulating what they would see if the object was being physically manipulated in the real world. As we have seen in previous chapters, viewing an object automatically activates the mental representation of that object. When watching an object physically rotate, the representation enables us to predict the end result of the movement based on previous experiences (Barsalou, 2008). When mentally imagining the movement, even when not visually presented with an object, the visual image that the individual creates is sufficient to activate the representation and the corresponding spatial pattern of movement expected from that object, resulting in the same anticipatory movements and physical constraints as found in actual physical rotations (Kosslyn et al, 1998). This suggests that mental rotation and physical rotations are performed using the same neural mechanisms and suffer from the same physical constraints. If this is indeed the case, then regardless of the type of stimuli that is being rotated, motor processes should be activated in order to facilitate the mental rotation process (Moreau, 2013).

Research suggests that when we perform a mental rotation of an object, we imagine it to be physically manipulated in some way resulting in the mental simulation of action (Kosslyn et al, 1998). If this is indeed the case, then motor cortex activations should occur during these types of mental rotation. However, comparative research between the rotation of 3D objects and images of hands suggests that we recruit different mechanisms in order to perform these transformations, not all of which require activation of the motor cortex to complete. In Kosslyn et al's (1998) study, participants were required to perform mental rotations of 3D abstract objects and images of hands. When performing mental rotations of hands, significant activation was found in the motor cortex; however no motor activation was found when participants were rotating the objects. When participants performed mental rotations of hands, there was activation in the motor areas associated with grasping movements and the preparation of reaching actions, however when mentally rotating objects, there was activation in the areas involved in determining the orientation of an object in order to guide a reaching movement but no activation of any movements themselves. This suggests that the mental rotation of objects recruits areas involved in spatial processing in order to accurately complete the task, which suggests that in these types of tasks, participants rely upon visual rather than motor techniques in order to make an accurate decision. The results of this study suggest that the processes used for performing mental rotations depend upon the type of stimuli being manipulated- when performing a mental rotation of a body part, the individual will visualize what their own body part would look like if manipulated and try to mentally bring it into line with the stimuli presented. As a result, motor activations are found in these studies as the simulation results in activation of the body part and corresponding movements, minus the overt action (Parsons et al, 1995). When presented with 3D abstract objects, however, there are a number of potential mental processes that one can use in order to perform the mental rotation that don't necessarily recruit the motor cortex. Individuals can imagine that they themselves are physically manipulating and rotating the object, thereby resulting in activation of the motor cortex. Alternatively, they can imagine that another individual is performing the rotation or that the object is moving by itself without any overt interaction. As a result, motor cortex activation would only occur if the individual imagines themselves to be an active force in the rotation (Kosslyn et al, 1998). Chu and Kita (2011) suggest that motor techniques can be employed in mental rotation tasks when visual techniques fail.. They found that when participants were encouraged to use physical gestures to solve motor rotation tasks they solved significantly more tasks correctly than when gestures were only allowed but not actively encouraged or when gestures were prohibited. They suggest that physical gestures are implemented when participants struggled with the task, which suggests that motor mechanisms are employed to solve these problems when visual or spatial techniques fail. This suggests that motor activations may also occur during abstract object rotation when we are unable to solve it in a spatial way, suggesting that motor activations are a fall back resource used when required.

When performing a mental rotation, we mentally simulate the physical action in our mind; this simulation is both visual and motor based, resulting in the activation of the visual properties of the object, which includes what it will look like when rotated, along with motor actions involved with the physical rotation of the object (Kosslyn et al, 1998). As a result, the areas involved with the physical interaction will be potentiated, resulting in increased readiness to perform the action and faster responses when that action is subsequently required. The aim of this series of studies is to determine whether restricting movements compatible with interaction with an object interferes with the simulation of actions when using the mental rotation process. In the following studies, participants were required to perform a Shepard and Metzler (1971) based task involving judging whether a 3D abstract shape would fit in a given aperture if rotated or whether it is a mirror image. As previously mentioned, the mental rotation of an abstract 3D object results in the activation of brain areas involved in spatial mapping and object orientation but does not potentiate any actual overt actions (Kosslyn et al, 1998). We aim to manipulate this by framing the visual scene as an interactable scene with objects that require physical manipulation to rotate. In the typical Shepard and Metzler (1971) task, participants are presented with two abstract 3D objects rotated at differing degrees and are required to judge whether they are the same or mirror images of each other. In this task the participants will be instructed to determine whether the object would fit into the hole if placed into it. This is to manipulate the participant's view of the object as being an interactable object rather than a visual stimulus, in order to trigger activation in the motor areas involved in transporting and interacting with the object physically. The participants will again have their grasping ability restrained in these experiments thereby reducing their ability to perform the real life movement required for interaction with the object. Objects will be presented at varying degrees of orientation and therefore will require mental rotation in order to judge whether the object is the same or a mirror image. If ability to perform mental rotation is dependent upon current physical capabilities and the ability to act, it is predicted that response times in the restricted condition will be significantly slower than in the no restricted condition due to disruption in the action simulation and the mental rotation of objects. It is also predicted that restricting hand movements will result a significant interaction between restriction conditions and object presentation conditions, as disturbing the mental rotation process should also eradicate the advantage that unmirrored objects have over mirrored objects. Mental rotations of unmirrored objects are typically performed in a linear rate in line with physical movements, with faster rotations towards degrees closest to the aperture increasing with the degree of rotation. Mirrored objects, however, typically require full rotations before a decision is made, therefore reaction times towards these stimuli tend to be stable across rotations at a much high rate than the unmirrored objects (Parsons, 1994). If restriction interferes with mental rotation ability, we predict that unmirrored objects will responded to in the same way as mirrored objects, as mental rotation using motor activations should be disturbed, therefore response times will become stable across all angles of rotation resulting in the removal of the advantage of angles closest to the aperture in relation to reaction times

3.1 Experiment 4a: Mental rotation of 3D objects

3.1.1 Introduction

Previous mental rotation research has shown that in order to mentally rotate an object, we simulate the physical movement that would be performed if executing that movement in the real world (Parsons, 1994). In this study it was predicted that if the simulation of physical actions is required when performing mental rotations, they should be significantly harder to perform when hands are constrained, resulting in longer reaction times in restricted compared to non-restricted conditions because the action that is required if performing in a real life situation is inhibited coupled with significantly more errors. This was tested by restraining participants' grasping movements when performing mental rotations of abstract 3D objects. In the present study, participants were required to judge whether a 3D object would fit into the hole next to it. In order to determine whether preventing participants from physically performing the movements associated with the task, participants had their hands and wrists strapped down in order to restrain the main movements required to interact with the object. Previous research into mental rotations has demonstrated a significant effect of body posture on rotation ability therefore in order to prevent any potential effects of posture on ability, participants' hands will remain in the same posture when unrestrained (Parsons, 1994).

The stimuli used for this experiment consist of 3D images of the letters F, Z, L and P designed to look like they are made from wood in order to maximise the appearance of them being manipulatable physical objects compared to abstract visual shapes. The typical mental rotation paradigm involves participants deciding whether two objects are the same or mirror images of each other. Although the premise and design of this experiment is based on this paradigm, participants will be asked if the object fits into the hole next to it in order to maximise the physical components required for this study. Non fitting objects however will still be mirror images of the target object as in standard mental rotation paradigms.

3.1.2 Method

Participants

A total of thirty Psychology undergraduates from Plymouth University participated in this study as part of a course requirement for a compulsory module in Research Methods. It was specified at the recruitment stage that all participants must have normal to corrected vision due to the fact that they were required to view visual stimuli as part of the experiment. It was also requested at recruitment that participants must have full mobility in their arms, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. Finally, as foot responses were required for the entire experiment, it was specified that participants must have full mobility in their feet and wear appropriate footwear on the day to avoid any performance issues.

Materials

Stimuli

The stimuli consisted of 3D images of the letters F, Z, L and P positioned next to a 3D aperture of either the same or a mirrored orientation. Letter stimuli were used consistent with previous research into the mental rotation of abstract objects (Pellizer & Georgopoulos, 1993). The images were created using POVRay®. Each 3D shape was either identical in presentation to the accompanying aperture or a mirror image and was consistently presented on the right side of the screen, with the aperture positioned on the left side of the screen. The aperture was always presented in a horizontal position facing upwards, however the 3D shapes were

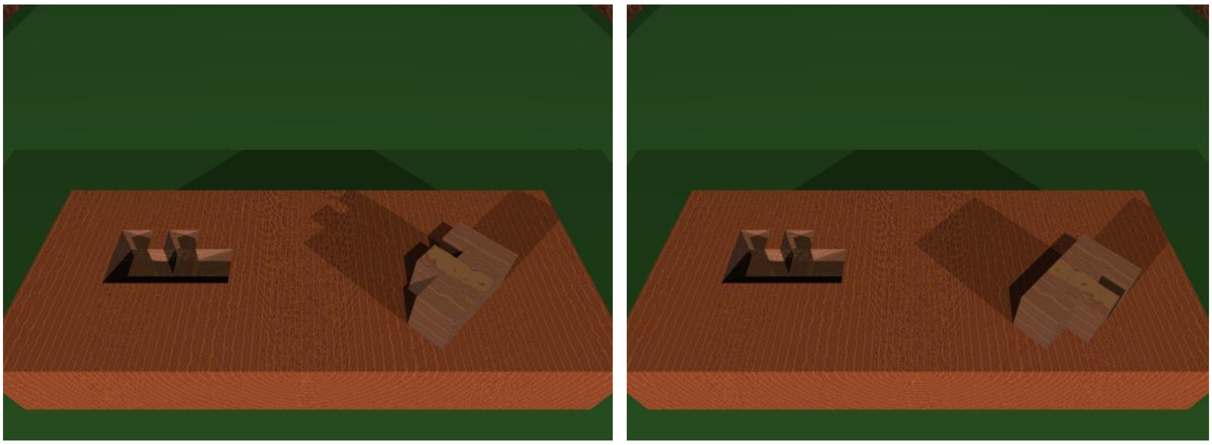


Figure 3.1*: Stimuli used in Experiment 4 with (l to r) non mirrored and mirrored trials*

presented in 8 different degree rotations from the test aperture- 0 (360) degree change from the aperture; 45°, 90°, 135°, 180°, 225°, 170°, 315°. The test images were designed to look like 3D objects placed on the surface of a table, with the aperture as a cut out hole. This was to manipulate participants' perceptions of the scenes as 3D interactable objects rather than visual images. Only one shape and test aperture was present in each trial. See Figure 3.1 for an example of the stimuli.

The experiment was developed using the Slide Generator 2007.3.3 program developed by Dr Mike Tucker of the University of Plymouth. It was performed on a Samsung Sync Master 2043 computer screen, with a screen resolution of 1680 x 1050 with 32bt colour quality. Responses were made using foot pedals developed by Herga Electric Limited connected to a parallel port. Foot pedals were located on the floor 300mm apart to mimic a comfortable foot position. Response allocation was equally balanced across participants, with half of participants using a left foot press for mirrored objects and half using the right foot press for mirrored objects.

Restriction

Participants performed half of the experiment with their hands and wrists restricted using Velcro straps to prevent them from being able to move their wrists and hands either horizontally or vertically. Participants' hands were placed underneath the straps palms facing downwards and securely restrained enough to prevent movement. Before beginning the experiment, participants were asked to demonstrate that they could not move their arms, wrists or hands. The order of restriction was balanced between participants, with half performing the first portion of the experiment under restriction and half performing it freely. Restriction order was analysed and had no significant effect on results.

Design and procedure

A within subjects design was used in which each participant was exposed to all conditions.   Participants were seated at individual desks with a computer screen and the foot response pedals on the floor with their left and right feet resting on the correct response pads. The chair was adjusted for individual comfort to enable comfortable manipulation of the foot pedals.   Participants were informed prior to the experiment that some restriction techniques would take place and were shown images replicating the restriction methods employed. Those in the restricted condition then had their hands secured under the restraints and were required to demonstrate that they could not move. The experimenter was present at all times during the procedure to ensure that the participants remained within the restraints and for safety reasons.

Each participant was required to perform 5 practice trials with the option of repeating this phase prior to the test trials. Successful completion of the practice phase was required before the experiment could begin. The stimuli scenes were presented individually on the screen and participants' were required to respond as quickly as possible using the appropriate foot response according to whether the object would fit into the hole as it is presented (with possible rotation) or whether the hole is a mirror image and therefore the object would need to be manually flipped in order for it to fit into the hole as presented. This was to manipulate participants' perception of the objects as being moveable and interactable, not just visual stimuli.

There were three conditions in this experiment; Restriction type (restricted or not restricted), Object presentation (mirrored or non-mirrored) and Object rotation from aperture (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). Restriction was blocked, with half of the participants performing under restriction for the first half of the experiment and without in the second half, and half performing without restriction for the first half and under restriction for the remaining trials. Object orientation and object rotation was randomised between slides and the sequence of stimuli presentation was randomised for each participant.

Each trial began with the appearance of a black screen for 500ms to indicate that the trial was about to begin. The stimuli were then presented. Each trial ended when a participant responded or 2000ms had elapsed. The stimuli remained visible until this occurred. A black screen was then displayed for 500ms before the beginning of the next trial.

3.1.3 Results

One participant was removed from the analysis because their error rate exceeded 10%. Error responses and RTs more than 2SDs from the participant's condition means were excluded from the analysis (total 9.04% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction (restricted/unrestricted), Object presentation (mirrored/unmirrored)

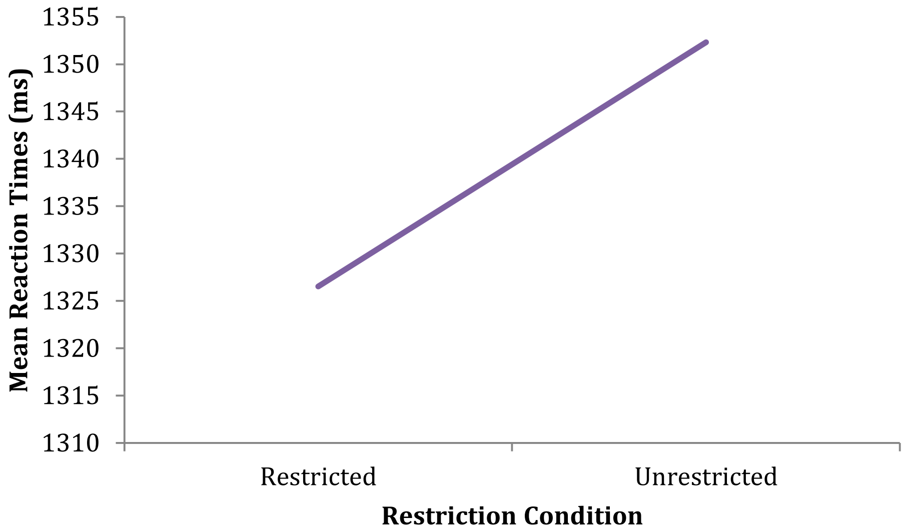


Figure 3.2: *Mean Reaction times (in ms) by Restriction condition*

and Object rotation from the aperture (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) (See Appendix 2 for full analysis).

Main effects

The analysis revealed significant main effects of Object Presentation and Object Rotation. Responses in the non-mirrored condition (M=1176ms) were significantly faster than responses in the mirrored condition (M=1502ms), F (1, 28) =97.577, p<0.001, η_p^2 =0.777. The main effect of rotation found that RTs were significantly faster in the degrees closest to the aperture (0/360°, 45°, 315°) compared to those furthest away (90°, 135°, 180°, 225°, 270°, 315°), F(7,196)=8.699, p<0.00, η_p^2 =0.237. There was no significant main effect of Restriction on RTs, F (1, 28) =0.270, p=0.607, η_p^2 =0.010 (**R- M=**1341.44ms, **SD=**588.86/ **UR- M=**1343.56, **SD=**572, Figure 3.2).

Interactions

The interaction between Object presentation and Object Rotation was significant, F (7,196) =18.304, p<0.001, η_p^2 = 0.395 (Figure 3.3). There was no significant interaction between Restriction and Object Presentation,

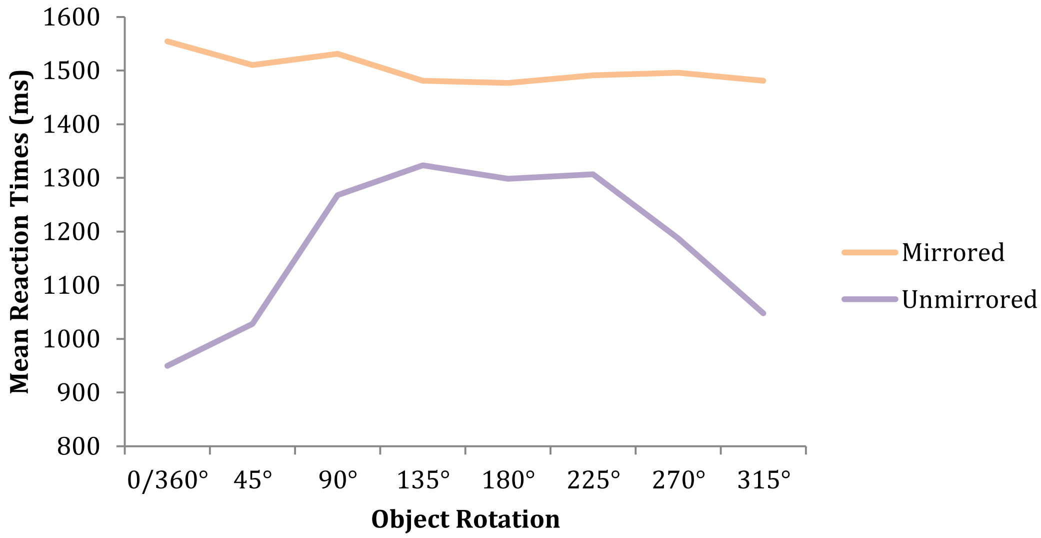
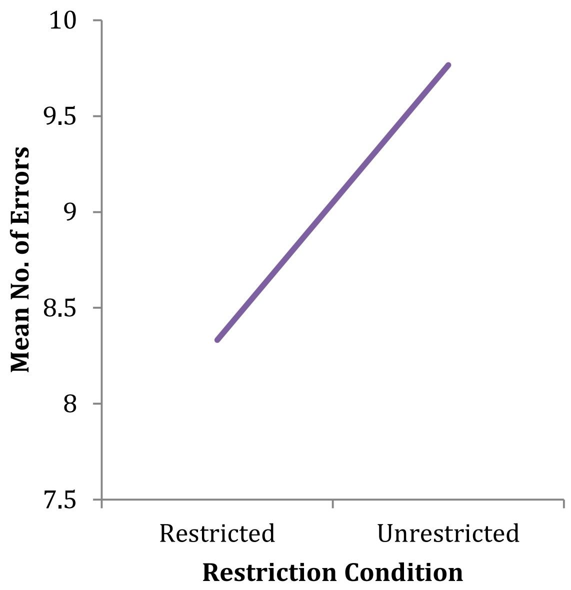


Figure 3.3: *Mean Reaction times (in ms) for Experiment 4a by Object Rotation and Object Presentation*

F (1, 28)=0.145, p=0.706, η_p^2 =0.005 or Restriction and Object Rotation, F (7,196) =0.477, p=0.851, η_p^2 =0.017. There was no significant three-way interaction between Restriction type, Object presentation and Object Rotation, F(7,196)=1.098, p=0.366, η_p^2 =0.038.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean error score data with within-participant factors of Restriction (restricted/unrestricted), Object presentation (mirrored/unmirrored) and Object rotation from the aperture (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The analysis found main effects of Object Presentation and Object Rotation on error rates. The main effect of Object presentation found that there were significantly more errors made in the Unmirrored condition (M=11.693) compared to in the mirrored condition (M=6.406), F(1,29)=17.616, p<0.001, η_p^2 =0.378. Pairwise comparisons of Object Rotation found that significantly more errors were made towards objects rotated furthest away



(L)Figure 3.4 : *Mean Number of Errors by Restriction Condition*

(R) Figure 3.5 : *Mean number of errors for Experiment 4 by Object Rotation and Object Presentation*

from the aperture (135°, 180°, 225°) compared to those closer to it (0/360°, 45°, 90°, 270°, 315°), F(7,203)=16.387,p<0.001, η_p^2 =0.361. There was no main effect of Restriction on error rates, F (1, 29) =1.167, p=0.289, η_p^2 =0.289 (**R- M=**8.333, **SD=**2.821 / **UR- M=**9.766, **SD=**3.042, Figure 3.4).

Interactions

There was a significant interaction between Object Presentation and Object Rotation, with significantly more errors made towards objects rotated furthest away from the aperture (90°, 135°, 180°, 225°) in the unmirrored presentations compared to in the mirrored condition, F(7,203)=18.936, p<0.001, η_p^2 = 0.395 (Figure 3.5). There was no significant interaction between Restriction and Object Presentation, F(1,29)=1.042, p=0.316, η_p^2 = 0.035, Restriction and Object Rotation, F(7,203)=1.411, p=0.203, η_p^2 =0.046 and no significant three-way interaction between Restriction, Object Presentation and Object Rotation, F(7,203)=0.815, p=0.575, η_p^2 =0.027.

3.1.4 Discussion

The aim of this study was to investigate whether restricting the ability to perform specific motor actions affects performance of motor imagery techniques, in this case the mental rotation of a 3D object. In this study, participants were required to respond with a left or right foot press according to whether a test object would fit into an aperture if rotated or whether it was a mirror image, whilst their hands and arms were restrained to prevent a reaching or grasping movement. In order to make an accurate judgment, previous research suggests that participants will access a mental representation of the object and use information regarding its movement ability in order to perform a mental rotation of the object. If participants imagine themselves to be performing a physical rotation of the object, activation should occur in the motor areas associated with this movement resulting in a motor simulation of the movement. According to our predictions, the body schema should represent this restriction and therefore it should be incorporated into the simulation of the movement, resulting in increased response times and error rates in the restricted conditions due to a disruption in physical rotation ability, which is subsequently reflected in mental rotation ability. The results showed that there was no significant effect of restriction on reaction times and no interactions between Restriction and the other experimental conditions, which suggests in this case that restricting movements involved in physical rotations of the objects does not significantly affect our ability to perform mental rotations of physical objects.

The results suggest a significant effect of object rotation on response times, with faster responses for objects whose degree of rotation is closest to the aperture orientation. This is in line with previous mental rotation research, which demonstrates a linear correlation between the degree of difference between the objects and response times for target object rotations of up to 180 ° (Shepard & Metzler, 1971). This finding is also in line with results found during physical manipulations and rotations of real objects, which provide support for the theory that mental rotations are bound the same physical constraints as physical rotations, suggesting that the same processes are recruited for both mental and physical rotations (Wraga, et al, 2010). These results suggest that mental rotation is taking place in this experiment; however, the lack of significant interaction between restriction type and rotation suggests that the restriction used in this study does not interfere with the mental imagery required for the task. It is possible that if individuals do not have experience of performing mental rotations such as these, then restricting the ability to perform an action would not interfere with their performance in these tasks. Further research could be conducted into this by investigating the effect of restriction on these tasks after practice of mental rotation techniques in order to investigate whether this is indeed a possibility.

The results suggest a significant main effect of object orientation, with faster responses for non-mirrored objects compared to mirrored objects. This finding is also in line with previous research, which demonstrated that the time it takes to determine whether an object is a mirror image of a rotated object is significantly longer than that of a non-mirrored object (Shepard & Meltzer, 1971). The results also indicate a significant interaction between object orientation and rotation angle, with a linear increase in reaction times as rotation angle increases up to 180^{o} in unmirrored stimuli but not in mirrored stimuli. This is attributed to the proposal that mirrored object require full rotation to determine whether they fit resulting in significantly increased response times, whereas unmirrored objects only need rotating until they fit with the target aperture. This suggests that mental rotation was taking place as predicted, however the lack of significant interaction between restriction type and object presentation again suggests that the restriction employed in this task does not interfere with the motor imagery required for the task.

In this study, participants were required to perform mental rotations of the visual stimuli. Previous research has found that mental rotations of visual objects do not always elicit activations in the motor cortex as individuals can perform the rotations using purely visual techniques (Kosslyn et al, 1998). The stimuli used in this experiment were designed to look like physical objects that can be manipulated in order to encourage activation in the motor cortex, however a possible explanation for the lack of significant findings could be that no explicit instructions were given to the individuals to imagine that they are physically interacting with the object and therefore other non-motor techniques may have been used instead. In order to control for this potential factor, Experiment 4a was replicated but participants were told to actively imagine themselves to be reaching out and physically manipulating the objects with their hands, in order to determine whether the temporary restriction of compatible movements affects the mental rotation of objects when active egocentric motor imagery is used to perform the mental rotations.

3.2 Experiment 4b: Mental rotation of 3D objects using active imagery

3.2.1 Introduction

The aim of Experiment 4b was to determine whether the lack of significant main effect of restriction demonstrated in the previous experiment was due to participants using non motor based techniques in order to perform the rotations, such as visual/spatial techniques or the input of another agent. In the previous experiment, participants were instructed to respond as to whether the object would fit into the hole next to it if rotated. This was to manipulate the participants to view the stimuli as a physical object that could be physically manipulated. It is possible that this was not the case in the previous experiment, therefore in this study participants were instructed to actively imagine themselves physically reaching towards the object and rotating it using their hands. As a result, this specific motor imagery should activate the motor areas involved in these movements (Parsons, 1994). It was predicted that restriction of these movements in the restricted conditions should lead to an update of the body schema and incorporation of this restriction into the simulations, resulting in longer reaction times and more errors in the restricted conditions.

3.2.2 Method

Participants

A total of thirty participants took part in this study. Paid participants were recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. It was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms and back, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia.

Materials

The same stimuli set; response mechanisms and computer program were used from the previous experiment.

Design and Procedure

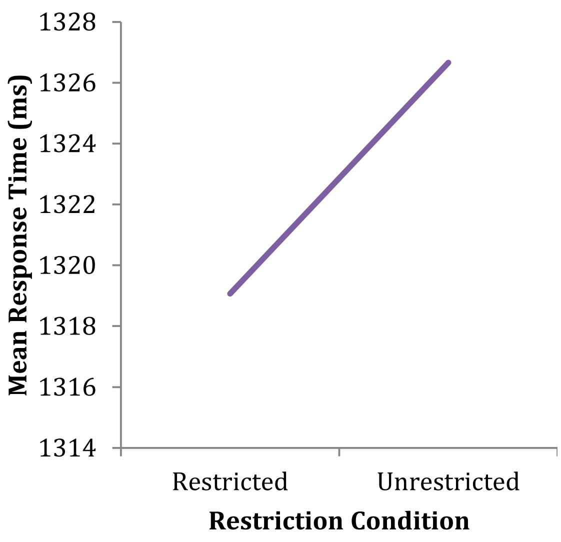
The design and procedure is identical to that in Experiment 4a, however participants were instructed to actively imagine themselves to be physically interacting with the objects.

3.2.3 Results

Two participants were removed from the analysis because their error rate exceeded 10%. Error responses and RTs more than 2SDs from the participant's condition means were excluded from the analysis (total 9.51% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted/unrestricted), Object presentation (mirrored/unmirrored) and Object rotation from the aperture (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°).

Main effects

The analysis revealed significant main effects of Object Presentation and Object Rotation. Responses in the non-mirrored condition (M=1165ms) were significantly faster than responses in the mirrored condition (M=1480ms), F (1, 27) =118.316, p<0.001, η_p^2 =0.814. The main effect of Rotation found that RTs were significantly faster in the degrees closest to the aperture (0/360°, 45°, 315°) compared to those furthest away (90°, 135°, 180°, 225°, 270°, 315°), F(7,189)=13.111, p<0.001, η_p^2 =0.327. There was no significant main effect of



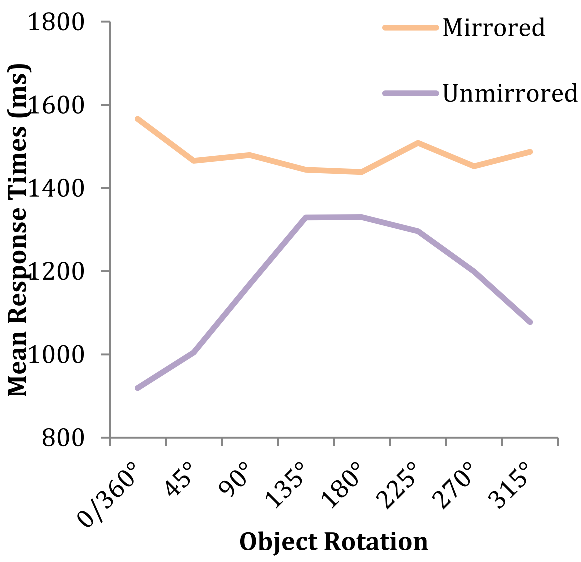


Figure 3.6: *Mean Response times (in ms) by Restriction Condition*

Figure 3.7: *Mean Response times (in ms) for Experiment 4b by Object Rotation and Object Presentation*

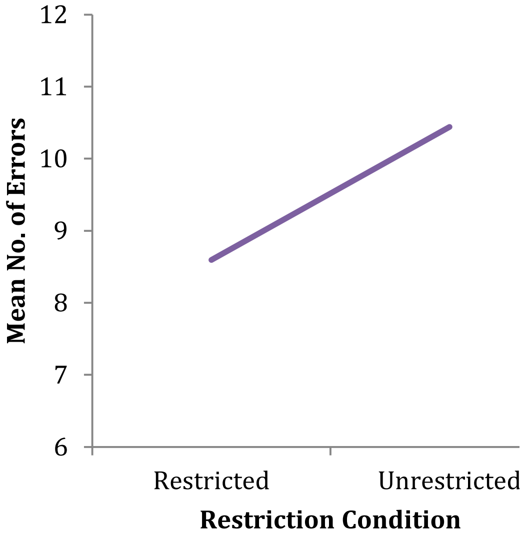
Restriction type on RTs, F (1, 27) =0.034, p=0.855, η_p^2 =0.001 (**R- M=**1339.21ms, **SD=**541.19/ **UR- M=**1359.13, **SD=**589.23, Figure 3.6).

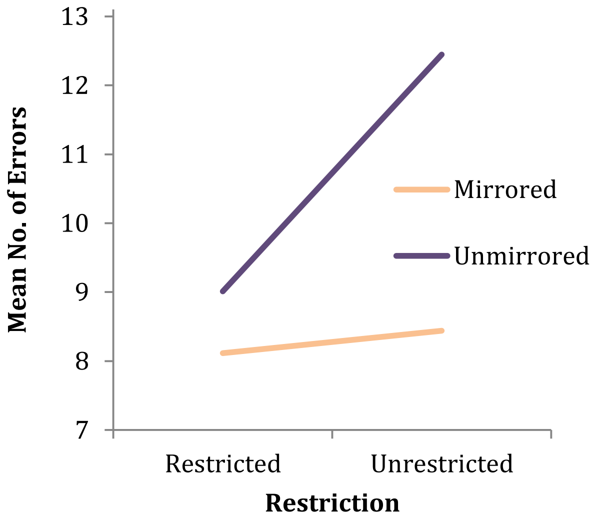
Interactions

The interaction between Object presentation and Object Rotation was significant, F (7,189) =26.795, p<0.001, η_p^2 =0.498 (Figure 3.7). There was no significant interaction between Restriction type and Object Presentation, F (1, 27) =0.074, p=0.787, η_p^2 = 0.003 or Restriction Type and Object Rotation, F (7,189) =1.305, p=0.250, η_p^2 =0.046. There was no significant three-way interaction between Restriction type, Object presentation and Object Rotation, F(7,189)=0.778, p=0.607, η_p^2 =0.028.

Error analysis

An ANOVA was performed on the mean error score data with within-participant factors of Restriction type (restricted/unrestricted), Object presentation





(L) Figure 3.8: *Mean number of errors by Restriction Condition*

(R) Figure 3.9: *Mean Number of errors by Object Presentation and Restriction*

(mirrored/unmirrored) and Object rotation from the aperture (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The analysis found main effects of Restriction type and Object Rotation on error rates. The main effect of Restriction found that there were significantly more errors made in the Unrestricted condition (M=8.350, SD=2.803) compared to in the restricted condition (M=6.880, SD=3.059), F (1, 29) =5.314, p=0.029, η_p^2 =0.155 (Figure 3.8). Pairwise comparisons of Object Rotation found that significantly more errors were made towards objects rotated furthest away from the aperture (135°, 180°, 225°) compared to those closer to it (0/360°, 45°, 90°, 270°, 315°), F(7,203)=12.079, p<0.001, η_p^2 =0.294. There was no main effect of Object presentation on error rates, F (1, 29) =3.119, p=0.088, η_p^2 =0.097.

Interactions

There was a significant interaction between Restriction and Object Presentation, F (1, 29) =4.653, p=0.039, η_p^2 =0.138 with more errors in the unrestricted condition than in the restricted condition towards unmirrored objects but no difference across restriction conditions towards mirrored objects (see Figure 3.9). There was also a significant interaction between Object Presentation and Object Rotation, with significantly more errors made towards objects rotated furthest away from the aperture (90°, 135°, 180°, 225°) in the unmirrored presentations compared to in the mirrored condition, F (7,203) =6.729, p<0.001, η_p^2 =0.188. There was no significant interaction between Restriction and Object Rotation, F(7,203)=0.856, p=0.543, η_p^2 =0.029 and no significant three-way interaction between Restriction, Object Presentation and Object Rotation, F(7,203)=0.828, p=0.565, η_p^2 =0.028.

3.2.4 Discussion

The aim of this study was to determine whether restricting movements involved in mental rotations affects our ability to perform the motor imagery required for such processes when active motor imagery is required. In this study, participants were instructed to visualize themselves physically reaching out and manually rotating the object in order to perform the mental rotation. The aim of this was to activate the motor areas involved in physical interaction with the object, in order to determine whether physically restricting these movements has a significant effect on the ability to perform mental rotations. The results of this study found that there was no significant main effect of Restriction on reaction times during mental rotations even when active imagery was required, which suggests that restriction of corresponding motor actions does not interfere with our ability to perform mental rotations of physical objects. Again, the results were consistent with previous mental rotation studies and showed a significant effect of Object presentation and Object rotation on response times, with significantly faster responses in the mirrored condition and in those degrees closest to the aperture presentation. This suggests that participants were performing mental rotations that abide by the constraints presented by physical interactions.

The results did indicate that restriction of compatible actions had a significant effect on error rates, with significantly more errors in the unrestricted condition compared to in the restricted condition. This is in the opposite direction to our predictions, which predicted larger rate of errors in the restricted condition due to the actions required for physical interaction being restricted, resulting in disruption to the simulation of those actions. An explanation of this result may be found in response conflict research. In this study, participants were told to actively imagine interaction with the object, which should lead to activation of the motor areas involved with that movement. In the unrestricted condition, participants' were physically able to move the body parts involved in the imagery and therefore the activation of those motor areas should potentiate those responses, making participants ready to act. However, in this experiment participants responded with their feet, therefore were primed to make foot responses to these stimuli resulting in increased activation in the foot area. This dual activation will not only increase cognitive load but could result in conflict between the two motor areas- participant are primed visually by the object to respond with a hand response but are required to respond with a foot response, leading to inhibition of the hand response (Mostofsky & Simmonds, 2008). In the restricted condition, the movements associated with interaction with the objects are unavailable thereby removing conflict between the hands and feet, resulting in fewer errors. In order to determine whether this is the case, this experiment was replicated with verbal responses used in replacement of foot responses, to determine whether restriction has an effect on mental rotation ability when no physical action response is required.

3.3 Experiment 4c: Mental rotation of 3D objects using voice responses

3.3.1 Introduction

The aim of Experiment 4c was to determine whether the lack of significant main effect of restriction on reaction times but the presence of a significant effect of restriction on error rates was due to response conflict between the hand actions primed by the motor imagery and the foot response required for response. In the previous experiments, participants responded with a left or right foot press, however in this experiment participants responded with verbal responses to determine whether restriction had the same effect on error rates when no limb responses were used. Based on previous research, it was predicted that when restricted, simulation of the rotation task should be disrupted, resulting in longer response times and significantly more errors in the restricted condition.

3.3.2 Method

Participants

A total of thirty participants took part in this study. Plymouth University students participated as part of a course requirement for a compulsory module in Research Methods. Paid participants were also recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. It was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms and back, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. It was also specified at recruitment that participants must speak English as their first language, to prevent any language effects.

Materials

The same stimuli set were used from the previous experiment. The responses in this study were made verbally; therefore responses were recorded using a voice response device developed by Herga Electric Limited, which was connected to a parallel port. The box has an inbuilt microphone and recorded a response from the onset of the word. The voice box recorded that a response had been made and actual responses were recorded manually. The responses were standardized across participants, with a "Yes" verbal response for an object that would fit in the aperture if rotated, and a "No" verbal response for an object that doesn't fit.

Restriction

The same restriction methods were used from the previous experiment.

Design and Procedure

The design and procedure is identical to that in Experiments 4a & b, however responses were made verbally.

3.3.3 Results

Six participants were removed from the analysis because their error rate exceeded 10% (total 20% of responses removed from the analysis). Error responses and RTs more than 2SDs from the participant's condition means were excluded from the analysis. The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted/unrestricted), Object presentation (mirrored/unmirrored) and Object rotation from the aperture (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°).

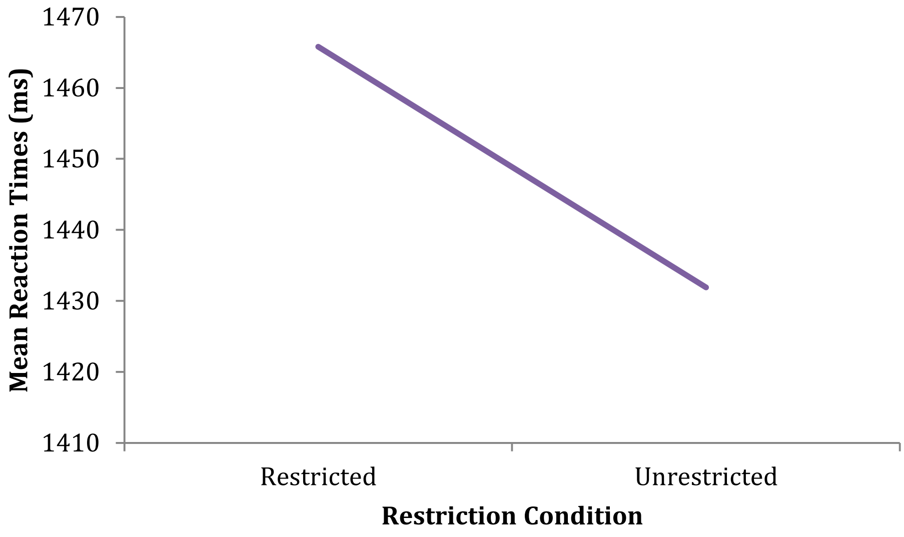


Figure 3.10: *Mean Response times (in ms) by Restriction Condition*

Main effects

The analysis revealed significant main effects of Object Presentation and Object Rotation. Responses in the non-mirrored condition (M=1286ms) were significantly faster than responses in the mirrored condition (M=1610ms), F (1, 23) =50.065, p<0.001, η_p^2 =0.685. Pairwise comparisons of object rotation found that RTs were significantly faster in the degrees closest to the aperture (0/360°, 45°, 315°) compared to those furthest away (90°, 135°, 180°, 225°, 270°, 315°), F(7,161)=4.930, p<0.001, η_p^2 =0.177. There was no significant main effect of Restriction type on RTs, F (1, 23) =0.668, p=0.422, η_p^2 =0.028 (**R- M=**1613.09ms, **SD=**623.86/ **UR- M=** 1526, **SD=**554.21, Figure 3.10).

Interactions

The interaction between Object presentation and Object Rotation was significant, F (7,161) =6.339, p<0.001, η_p^2 =0.216 (Figure 3.11). There was no significant interaction between Restriction type and Object Presentation, F (1, 23) =0.591, p=0.450, η_p^2 =0.025, or Restriction Type and Object Rotation, F (7,161) =1.250, p=0.279, η_p^2 =0.052. There was no significant three-way interaction between

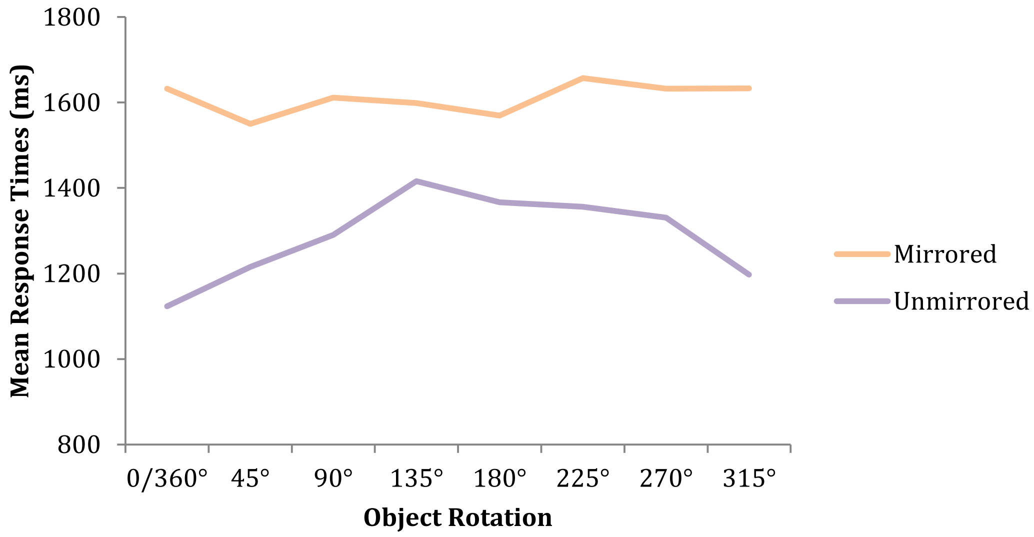


Figure 3.11: *Mean Response times (in ms) for Experiment 4c by Object Rotation and Object Presentation*

Restriction type, Object presentation and Object Rotation, F(7,161)=0.769, p=0.614, η_p^2 =0.032.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean error score data with within-participant factors of Restriction type (restricted/unrestricted), Object presentation (mirrored/unmirrored) and Object rotation from the aperture (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The analysis found main effects of Object Presentation and Object Rotation on error rates. The main effect of Object presentation found that there were significantly more errors made in the Unmirrored condition (M=20.443) compared to in the mirrored condition (M=9.036), F(1,29)=5.203, p=0.03, η_p^2 =0.152. Pairwise comparisons of Object Rotation found that significantly more errors were made towards objects rotated furthest away from the aperture (135°, 180°, 225°) compared to those closer to it

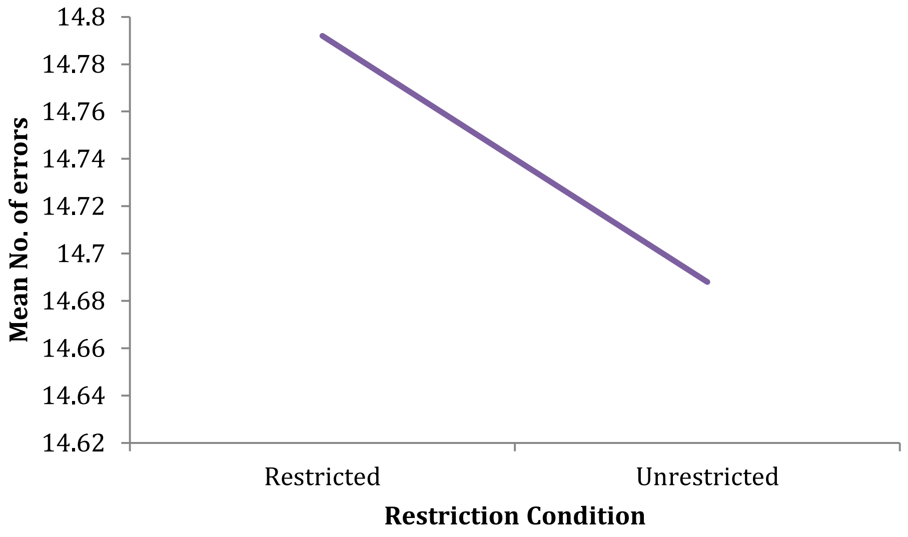


Figure 3.12: *Mean Number of Errors by Restriction Condition*

(0/360°, 45°, 90°, 270°, 315°), F(7,203)=4.113, p<0.001, η_p^2 =0.124. There was no main effect of Restriction on error rates, F (1, 29) =0.010, p=0.919, η_p^2 =0.000 (**R-M=**14.792,SD=23.11 / **UR- M=**14.688, **SD=**22.82, Figure 3.12).

Interactions

There was a significant interaction between Restriction type and Object Presentation, with fewer errors in the restricted condition and more in the unrestricted condition when objects are mirrored and fewer errors in the unrestricted and more in the restricted when the objects are in the unmirrored presentation, F(1,29)=5.477, p=0.026, η_p^2 = 0.159 (Figure 3.13). Post hoc comparisons using the Fisher LSD test revealed a near significant difference between restricted and unrestricted conditions when the objects were in a mirrored presentation (p=0.051) but no significant difference between restriction conditions when objects were in an unmirrored condition (p=0.193). There was also a significant interaction between Object Presentation and Object Rotation, with significantly more errors made towards objects rotated furthest away from the aperture (90°, 135°, 180°, 225°) in the unmirrored presentations compared to in the

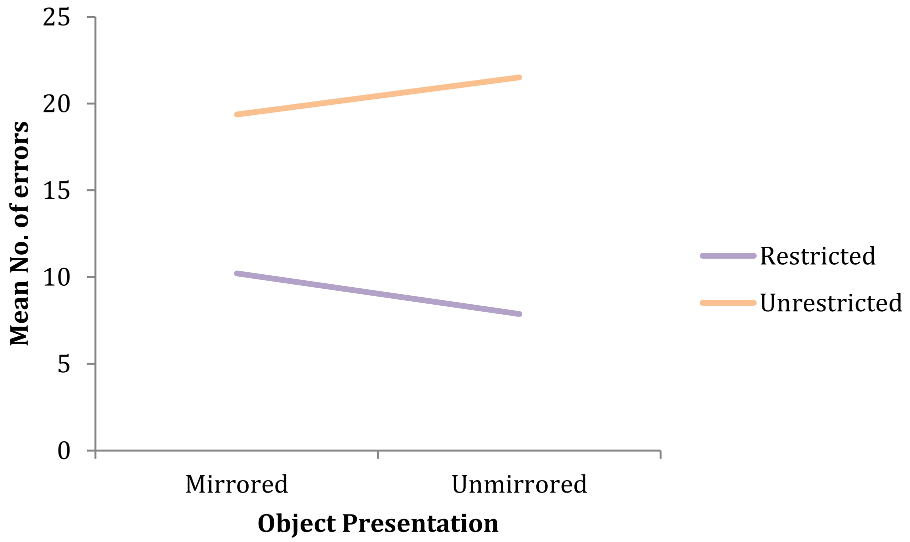


Figure 3.13: *Mean Number of errors for Experiment 4c by Object Presentation and Restriction type*

mirrored condition, F(7,203)=2.451, p=0.020, η_p^2 =0.078. There was no significant interaction between Restriction and Object Rotation, F(7,203)=1.038, p=0.405, η_p^2 =0.035 and no significant three-way interaction between Restriction, Object Presentation and Object Rotation, F(7,203)=0.1.575, p=0.144, η_p^2 =0.052.

3.3.4 Discussion

The aim of this study was to investigate whether restricting motor abilities involved in a mental rotation task affects our ability to perform the task when voice responses are required. The results of this study found that there was no significant main effect of Restriction on correct response times and no significant interactions between Restriction and any other of the experimental conditions. These findings suggest that the restriction of actions compatible with interaction with the stimuli did not influence participants' ability at performing this mental rotation task even when verbal responses were required.

Analysis of the error rates was consistent with the findings from previous mental rotation research, with significant main effects of Object Presentation and Object rotation on error rates. However, in contrast to the previous study, there was no significant main effect of Restriction on error rates. This would provide support for the theory posited in the previous experiment that the conflict of responses in Experiment 4b resulted in significant differences in the error rates in restricted and unrestricted conditions. Use of verbal responses in this experiment removed the competition previously found between the hand responses primed by the motor imagery and the foot responses required for response, which could explain the lack of significant effect of restriction on error rates as previously found in Experiment 4b.

The error analysis in this study also indicated a significant interaction between Restriction and object presentation, with more errors in the restricted condition when objects were mirror images and more in the unrestricted condition when objects were unmirrored. A possible explanation for this interaction is that when participants were restricted, the lack of availability of compatible motor actions resulted in participants resorting to visual rather than motor techniques in order to perform the rotations. As a consequence of this, unmirrored objects would be easier to make a judgment on as participants would be able to use a simple visual matching technique in order to accurately make a judgment, without the need to perform any rotations. When objects were mirrored, however, visual judgments would be more difficult to accurately perform resulting in higher error rates towards mirrored images in the restricted conditions. When participants are unrestricted, the availability of actions means that they would be able to use motor techniques to make an accurate judgment therefore they would be able to make accurate judgments of the mirrored stimuli, resulting in less errors in these conditions compared to unmirrored stimuli. These findings suggest that restricting motor actions may have an effect on the techniques used to perform mental rotation tasks, however further research would need to be conducted in this area in order to make affirm conclusion. This will be discussed further in the Discussion Chapter.

It is important to note here, however, that there were a large number of errors made in this study compared to previous studies. A possible explanation for this is that voice responses are more susceptible to interference effects in these tasks, therefore resulting in more error. This is a theory supported by Owens, Goodman and Pianke (1984) who found that when a group of naval aviators were required to respond to cognitive tasks using voice responses, they were significantly less accurate than when keyboard responses were required. This would therefore suggest that different response modalities are affected in differing ways by cognitive tasks- this is addressed in more detail in the Discussion chapter.

3.3.4 General Discussion

In these studies, participants were required to make a judgment regarding whether an object (in the form of a 3D abstract wooden shape) would fit into an aperture presented alongside it if rotated. In order to do this, research suggests that the individuals will simulate physical interaction with that object in order to perform a mental rotation which, coupled with information provided by the body schema of up-to-date physical capabilities, should enable the correct response to be made. If the simulation recruits information about current physical capabilities for its performance, restriction of actions associated with physical interaction with the object should disrupt the simulation process, resulting in significant differences in response times and error rates in the two restriction conditions.

It was predicted that the restriction of compatible movements would disrupt participants' ability to perform mental rotations of 3D objects and result in significantly larger response times in the restricted condition compared to the unrestricted conditions, coupled also with significantly more errors in the restricted condition. There were significant effects of Object Rotation and Object Presentation in all three studies, indicating that mental rotations were taking place along the continuous trajectory typically found in mental rotation studies, which indicates that mental simulation is taking place (Shepard and Metzler, 1971). However, that lack of significant interaction between restriction, rotation angle and object presentation on response times suggests that participants were able to perform mental rotations of objects at the same speed and accuracy regardless of whether their motor capabilities were restricted, suggesting that in this particular case, our ability to consciously simulate motor actions is not dependent upon our current physical capabilities.

The results of Experiments 4b and 4c indicated a significant interaction between Restriction and Object orientation in error rates, with significantly less errors towards unmirrored stimuli when restricted compared to unrestricted conditions and vice versa towards mirrored stimuli. We would expect in general to find larger error rates when restricted due to the lack of availability of using motor imagery techniques to complete the rotations. These results, however, suggest that in some conditions the reverse is actually the case, with less errors made when restricted compared to when unrestricted. A possible explanation for this could be that as restriction prevents the use of motor imagery taking place, participants revert back to visual strategies in order to complete the task, thereby removing any participatory effect of the restriction and resulting in less errors when restricted. When unrestricted, however, the motor codes are available for use and therefore motor imagery takes place. The interaction indicated that less errors were made towards unmirrored stimuli in both experiments when participants were restricted compared to when unrestricted. As rotations of these stimuli are typically the easiest to perform this would suggest that motor activations are not necessarily required for successful completion of these rotations and in fact are facilitated when only visual techniques are applied. In contrast to this, responses towards mirrored stimuli in these studies are typically more difficult to perform and are therefore may be more susceptible to the influence of the restriction. This finding suggests that our cognitions use motor imagery in situations where it is not the most effective method which indicates that we do not always select the process that is most effective for completing a task. This could suggest that the body automatically takes over performance in these tasks, suggesting a hierarchical process whereby the body is automatically involved and visual techniques are only employed when this is not possible. It is obvious that further research would need to be conducted in this area before any firm conclusions can be made but this does suggest that our cognitions are not yet sophisticated enough to determine the most effective method for completing cognitive tasks.

One of the possible explanations for the lack of significant interaction between restriction and rotation angle found in these studies could be that despite the attempts to manipulate participants' perceptions of the stimuli as being manipulatable physical objects, participants may still have viewed the objects as visual stimuli and therefore used purely visuo-spatial techniques to perform the transformations. Previous research suggests that mental rotations are performed by imagining the stimuli to be “manipulated” in some way, either by the individual themselves, another person or by an active agent that causes the rotation to occur (Kosslyn et al, 1998). The type of cortical activation that one would expect to occur would therefore depend on which strategy the individual employs. Research into this area would suggest that during the mental rotation of body parts and objects, individuals imagine manipulating their own corresponding or action compatible body parts in order to simulate the rotation whereas the mental rotation of abstract objects is often imagined to take place independently from any motor input from the individual (Vingerhoets, de Lange, Vandemaele, Deblaere & Achten, 2002). As a consequence of this, activation of the motor cortex would only be expected when rotating manipulatable objects or body parts. In this study, wooded letters were used to represent manipulatable objects; however it is possible that as this type of stimuli does not have any specific action associated with it the only action simulated would be that involved in physically rotating the object. If participants used visuospatial techniques to perform the judgements, it is possible that motor activations did not occur in this study. Future research in this area could focus on the effect of restriction on the mental rotation of familiar objects in order to determine whether the mental rotation of objects with specific action associations is significantly influenced by action availability.

In conclusion, the restriction of hand actions was not sufficient to disrupt the mental rotation of 3D objects. It is possible that motor processes were not involved during this task; therefore the next series of studies aims to look at the effect of restriction during the mental rotation of body parts, a process that research has shown to directly involve the motor system.

Chapter 4- Exploring the relationship between Hand Rotations and action availability

Introduction

The previous experiments focused on the mental rotation of 3D objects in order to determine whether restricting the actions compatible with physical rotation of the object disrupts the mental simulation of the rotation action. This next series of experiments aims to investigate whether restricting actions has a significant effect on our ability to perform mental rotations of body parts compatible with the body part being restricted.

The mental rotation of body parts has been extensively studied in recent years and is used as an example of motor imagery, as research has shown that the same cortical activations occur when performing mental rotations of body parts as when physically performing those rotations (Parsons, 1987 a, b). In standard body part mental rotation studies, participants are presented with an image of a body parts rotated at varying degrees and are required to respond according to its laterality by performing a mental rotation of the stimuli. Research into the mental rotation of body parts suggests that when performing these mental rotations, we mentally simulate moving our own body part until it falls into line with the image being rotated in order make an accurate judgement (Parsons, 1987 a, b). As a consequence of this, mental rotations of body parts suffer from the same physical constraints as actual movements. Cooper and Shepherd (1975) found that when required to judge the laterality of rotated hands, participants were significantly faster at making judgements when the rotation required was compatible with real life movements compared to when the rotation required was physically uncomfortable or even impossible to perform. These findings suggest that when performing these rotations, participants will access information contained in their body schema regarding their physical limitations and will use this in order to perform the simulation. When the rotation is impossible to physically perform, this information will be represented in the schema and reflected in the simulation, resulting in slower performance of the mental rotation. This series of experiments will look at the effect of temporarily restricting movements on our ability to perform mental rotations of body parts.

Research into the mental rotation of hands has discovered that hand posture has a significant effect on our performance at mental transformations of corresponding body parts. Parsons(1994) found that when required to make laterality judgements of hand stimuli presented in a palm upwards position, participants were significantly impaired at performing the mental rotations when their own hand was in a palm down orientation. Similar studies have-found that manipulating the positioning of participants' hands during mental rotation tasks using hand stimuli can have a significant effect upon judgement times. In a study by Ionta, Fourkas, Fiorio & Aglioti (2007), participants were required to make laterality judgements of hand stimuli with their hands positioned either behind their backs or resting on their knees. The results found that the mental rotations were significantly faster when participants hands were positioned in front of then compared to when they were positioned behind their back. The findings of these studies support the theory that the mental rotation of body parts is conducted by mentally simulating movement of one's own hand in order to bring it in to line with the position of the stimuli being judged. The increased response times found when hand posture is incompatible with the stimuli orientation suggest that the simulation represents the actual movements required if the individual was to perform them physically at that moment in time, therefore the increased response times are indicative of the increased time it would take to move their hands from their current position to the one required for transformation. These findings provide support for the relationship between body posture and motor imagery performance, suggesting that both biomechanical and enforced constraints influence our performance during the simulation of movements.

Previous research investigating the effects of bodily constraints on the mental rotation of body parts have typically focused on the effect changes to the posture of compatible body parts has on mental rotation performance (Parsons, 1994). The results of these studies suggest that the disruption in mental rotation ability found when hand posture is manipulated is due to the increased time it takes to perform the simulation of the rotation from hands behind the back to the presented orientation (Ionta et al, 2007). This next series of experiments aims to determine whether similar disturbances to the mental rotation of hands are found when the body posture stays the same but the ability to move is manipulated. If this is the case, then it can be concluded that the disruption in mental rotation ability found in previous mental rotation studies could also be due to the fact that the physical movement simulated in the mental rotation is not available and therefore the simulation of the physical behaviour is prevented. The restriction method in the following studies consisted of strapping participants hands in a palm down orientation. As these studies were interested in the effect of preventing movement on mental rotation ability, it was crucial that there was no change in hand posture between the restriction conditions; therefore during the unrestricted conditions participants rested their hands in exactly the same position as during the restricted condition. The restriction method completely restricted participants' movements and participants were asked to demonstrate before taking part in the experiment that they were completely restrained. This was partly to ensure that complete restraint was taking place but also to maximise the representation of the restriction in the body schema through increased sensory motor activations. In order to prevent participants from using visual techniques such as looking at their own hands in order to determine the correct answer, participants' hands were not visible to participants at all time during the experiments.

In this series of studies, it is predicted that the mental simulation of the rotation movement will be disturbed when participants are restricted because the body schema will represent the fact that compatible movements are unavailable for performance, which should then be reflected in the simulation of movement. If these studies demonstrate a significant difference in reaction times between reaction conditions when the only element of the experiment that changes is the restriction, it can be concluded that the difference in reaction times is due to the fact that the corresponding motor action is not available to be performed, resulting in a disturbance in the simulated behaviour.

4.1 Experiment 5a: Mental rotation of hands

4.1.1 Introduction

The aim of this study is to investigate whether restricting movement in the hands of participants has a significant effect on their ability to perform mental rotations of hand stimuli. The paradigm for this study is based on that used by Ganis, Keenan, Kosslyn and Pascual-Leone (2000). In a change from the traditional hand laterality judgement tasks usually used to investigate mental rotation of hands, participants were presented with two images of hands and were required to respond according to whether the hands are the same or different to each other. This experiment follows the same format as typical object mental rotation studies in that participants make comparisons between two stimuli regarding their similarity, as opposed to making judgements of individual stimuli. The results showed activation in the left primary motor cortex during the mental rotation task, therefore participants used motor rather than purely visual techniques in order to make accurate judgements. In the current study, participants will be presented with two images of hands rotated at varying degrees from each other and will be required to judge whether the hands are the same or different whilst restrained, in order to determine whether restricting the ability to perform physical hand rotations significantly effects participants ability to perform mental rotations of the corresponding body part.

According to previous motor rotation research, it is predicted that in order to accurately respond as to whether the two hands are the same or different, participants will perform a mental rotation of the target hand to bring it into line with the test hand. In order to perform this mental rotation, individuals will access the mental representation of the hand which will contain information regarding its motor capabilities provided by the body schema. This will then result in a mental simulation of a physical hand rotation, which is indicated by increased activation in the motor cortex. It is predicted that when participants are unable to perform the physical equivalent of the rotation task, i.e. during restricted conditions, the restriction will be evident in the body schema and will be represented in any subsequent simulated movement, resulting in longer reaction times during the restricted conditions compared to unrestricted trials. It is predicted that responses towards unmirrored (the same) hands will be significantly faster than towards mirrored hands, as research suggests that mirrored stimuli require a full rotation before an accurate judgement can be made, resulting in increased response times towards these stimuli; however it is also predicted that restricting hand movements will result a significant interaction between restriction conditions and hand presentation conditions, as disturbing the mental rotation process should also eradicate the advantage that unmirrored hands have over mirrored hands. Finally, it was predicted that significantly more errors will be made in the restricted compared to the unrestricted conditions due to a disruption in rotation ability.

4.1.2 Method

Participants

A total of thirty Psychology undergraduates from Plymouth University participated in this study as part of a course requirement for a compulsory module in Research Methods. It was specified at the recruitment stage that all participants must have normal to corrected vision. It was also requested at recruitment that participants must have full mobility in their arms and back, with no history of any chronic pain, strokes or immobility conditions such as arthritis or dystonia. Finally, as foot responses were required for the entire experiment, it was specified that

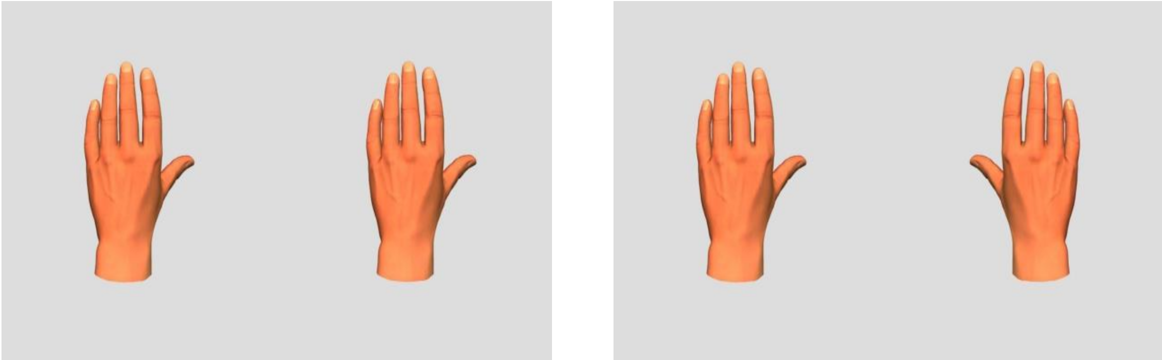


Figure 4.1: *Stimuli used in Experiment 5a with (l to r) non-mirrored and mirrored trials- Permission to reproduce this image has been granted by N. Brady*

participants must have full mobility in their feet and wear appropriate footwear on the day to avoid any performance issues.

Materials

Stimuli

3D computer generated images of a white hand developed by Choisdealdha, Brady and Maguinness (2011) (also cited in Brady, Maguinness & Choisdealdha, 2011) were selected for this experiment. The stimuli set consisted of left and right hands presented with their palms facing downwards. The left hand stimuli were mirror images of the right, therefore stimuli were identical in all aspects apart from handedness. Each experimental scene consisted of two hands- the hand on the left of the screen was consistently presented in the upright position with its palm facing downwards, whereas the hand on the right was rotated in 8 different degree rotations- 0 (360) degree change from the test hand; 45°, 90°, 135°, 180°, 225°, 170°, 315°. The stimuli were approximately 20cm by 15cm in order to mimic real hands. The stimuli were presented in colour on a white background. Examples of the stimuli are shown in Figure 4.1.

The experiment was developed using Slide Generator 2007.3.3 developed by Dr Mike Tucker of the University of Plymouth. It was performed on a Samsung Sync

Master 2043 computer screen, with a screen resolution of 1680 x 1050 with 32bt colour quality. Responses were made using foot pedals developed by Herga Electric Limited connected to a parallel port. Foot pedals were located 300mm apart to mimic a comfortable foot position. Response allocation was equally balanced across participants, with half of participants using a left foot press when the hands are the same and half using a left foot press when the hands are different.

Restriction

Participants performed half of the experiment with their hands and wrists restricted using Velcro straps to prevent them from being able to move their wrists and hands either horizontally or vertically. Participants' hands were placed underneath the straps palms facing downwards and securely restrained enough to prevent movement. Before beginning the experiment, participants were asked to demonstrate that they could not move or rotate their arms, wrists or hands. The straps were positioned 300mm apart. In non-restricted trials, participants' hands and wrists rested in the same position but were not secured down, ensuring that the hand posture remained the same for both conditions. The order of restriction was equally balanced between participants, with half performing the first portion of the experiment under restriction and half performing it freely. This was to ensure that restriction order did not influence the results.

Design and procedure

A within subjects design was used in which each participant was exposed to all conditions. Participants were seated at individual desks with a computer screen and the foot response pedals on the floor with their left and right feet resting on the correct response pads. The chair was adjusted for individual comfort to enable comfortable manipulation of the foot pedals. Participants were informed prior to the experiment in both the Brief and verbally that some restriction techniques would take place and were shown images replicating the restriction methods employed. Those in the restricted condition then had their hands secured under the restraints and were required to demonstrate that they could not move. The experimenter was present at all times during the procedure to ensure that the participants remained within the restraints and for safety reasons.

Each participant was required to perform 5 practice trials with the option of repeating this phase prior to the test trial. Successful completion of the practice phase was required before the experiment could begin. The stimuli scenes were presented individually on the screen and participants were required to respond as quickly as possible using the appropriate foot response according to whether the hand on the right of the screen was the same as the hand on the left or different.

There were three conditions in this experiment; Restriction type (restricted/unrestricted), Presentation (mirrored/non-mirrored), and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). Restriction condition was blocked, with half of the participants performing under restriction for the first half of the experiment and without in the second half of the experiment, and half performing without restriction for the remaining trials. Presentation and Rotation was randomised between slides and the sequence of stimuli presentation was randomised for each participant.

Each trial began with the appearance of a white background for 500ms to indicate that the trial had begun, after which the stimuli were presented. Each trial ended when a participant responded or 3000ms had elapsed. The hands remained visible until this occurred. A grey screen was presented for 500ms before the beginning of the next trial.

4.1.3 Results

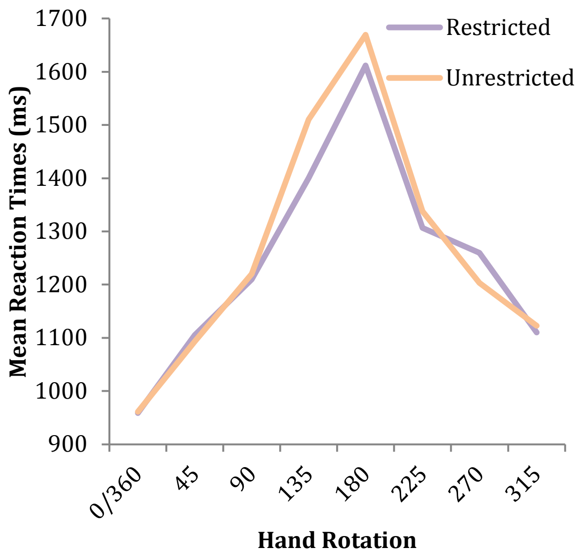
Six participants were removed from the analysis because their error rate exceeded 10%. Error responses and RTs more than 2SDs from the participant's condition means were excluded from the analysis (total 20% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted/unrestricted), Hand presentation (mirrored/non mirrored) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) (See Appendix 3 for full analysis)..

Main effects

The analysis revealed main effects of Presentation and Rotation on response times. Responses in the mirrored condition (M=1325ms), when the two hands differed in laterality, were significantly slower than responses in the non-mirrored condition (M=1184ms), F(1,23)=32.770, p<0.001, η_p^2 =0.588. The main effect of Rotation found a significant increase in RTs as rotation angle increased up to 180°, F(7,161)=46.947, p<0.001, η_p^2 =0.671. There was no significant effect of Restriction on RTs, F(1,23)=0.330, p=0.571, η_p^2 =0.014 (**R- M=**1248.98ms, **SD=**557.39/ **UR-M=**1251.03, **SD=**605.05, Figure 4.2).

Interactions

There was a significant interaction between Restriction and Rotation, F(7,161)=2.154, p=0.041, η_p^2 =0.086, with longer reaction times towards rotations furthest from the test stimuli in the unrestricted compared to restricted conditions (Figure 4.3). Post hoc comparisons using the Fisher LSD revealed that that were significant differences between response times at the 135^{o} rotations across restriction conditions (p=0.008) but no significant differences between the other



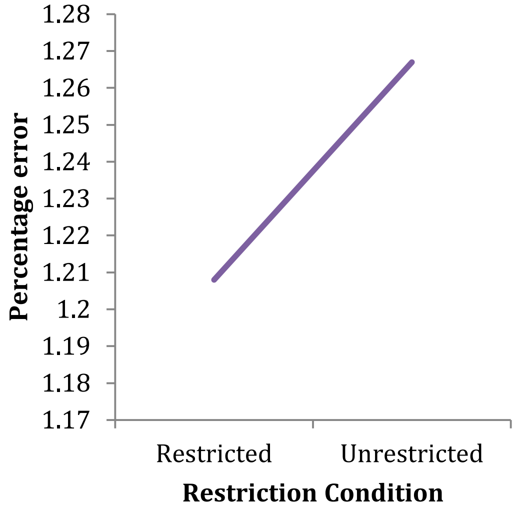
(L) **Figure 4.2**: *Mean Reaction times (in ms) for Experiment 5a by Restriction Condition*

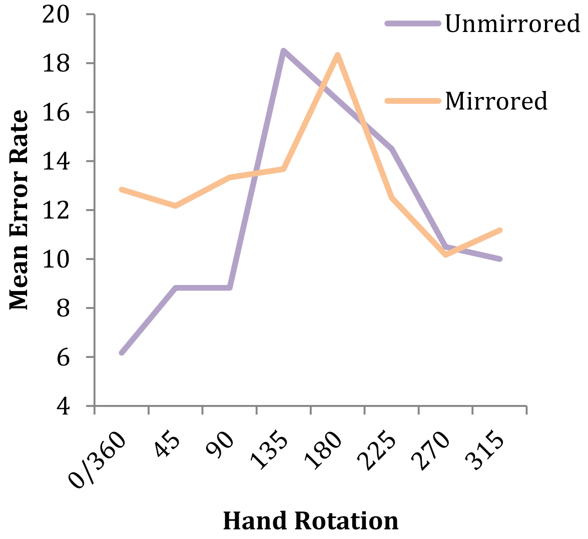
(R) **Figure 4.3**: *Mean Reaction times (in ms) for Experiment 5a by Object Rotation and Restriction*

rotation angles across restriction conditions (p>0.05). There was no significant interaction between Restriction and Presentation, F(1,23)=.385, p=0.541, η_p^2 =0.016, or Presentation and Rotation, F(7,161)=0.410, p=0.895, η_p^2 =0.018. There was no significant three-way interaction between Restriction type, Hand presentation and Rotation, F(7,161)=1.633, p=0.129, η_p^2 =0.066.

Error analysis

An ANOVA was performed on the mean error score data with within-participant factors of Restriction type (restricted/unrestricted), Hand presentation (mirrored/unmirrored) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The analysis found main effects of Rotation on error rates. Pairwise comparisons of Rotation data found that significantly more errors were made towards objects rotated furthest away from the test hand (135°, 180°, 225°) compared to those closer to it (0/360°, 45°, 90°, 270°, 315°), F(7,203)=9.628,





(L) Figure 4.4: Mean Error rate (in percentages) for Experiment 5a by Restriction Condition

(R) Figure 4.5: Percentage Error rate for Experiment 5a by Hand Rotation and Presentation

p<0.001. η_p^2 =0.213. There was no main effect of Restriction, F(1,29)=1.170, p=0.288, η_p^2 =0.039 (**R- M=**12.08, **SD=**19.79/ **UR- M=**12.67, **SD=**19.26, Figure 4.4) or Presentation, F(1,29)=1.028, p=0.319, η_p^2 =0.034 on error rates.

Interactions

There was a significant interaction between Presentation and Rotation, F(7,203)=2.668, p=0.012, η_p^2 =0.084 (Figure 4.5). There were no significant interactions between Restriction type and Presentation, F(1,29)=0.064, p=0.803, η_p^2 =0.002, or Restriction and Rotation, F(7,203)=1.148, p=0.335, η_p^2 =0.038, and no significant three-way interaction between Restriction type, Hand presentation and Rotation, F(7,203)=1.168, p=0.323, η_p^2 =0.039.

4.1.4 Discussion

The aim of this study was to investigate whether restricting the ability to perform physical hand rotations affects performance of mental rotations of hand stimuli. In this study, participants were required to respond with a left or right foot response according to whether the hand stimuli presented were the same or different whilst their hands were restricted to prevent ability to perform a physical hand rotation movement. In order to make an accurate judgement, previous research suggests that individuals will perform a mental rotation of the target hand by mentally simulating the movement using their own hands. If the simulation relies upon current physical capabilities in its performance then we should expect to see an effect of restriction on mental rotation performance. The results showed that there was no significant effect of restriction on restriction times, which suggests that restricting the participants' ability to perform a physical hand rotation does not interfere with the overall speed at which participants are able to perform mental rotations of the same stimuli. There was, however, a significant interaction between Restriction and Rotation, which found that responses were faster towards the rotations around 180° in the restricted condition compared to during the unrestricted condition, which suggests that restricting the ability to perform mental rotations of objects significantly affected participants ability to perform mental rotations. This interaction was in the opposite direction predicted, as it was previously proposed that restricting physical actions compatible with the mental rotation would result in a disruption to the mental rotation processes, resulting in increased judgement times in the restricted conditions. A possible explanation for this can be found in previous mental rotation research. Cooper and Shepherd (1975) found that participants were significantly faster at making judgements when the rotation required was compatible with real life movements compared to when the rotation required was physically uncomfortable to perform. The degrees of rotation around the 180 degree mark are those that are uncomfortable/impossible to perform and this is represented in the body schema. This discomfort is subsequently reflected in the simulation, typically resulting in slower performance of the mental rotation towards these rotations. In the current study it was predicted that the restraint should disrupt the simulation of rotations, however it is possible that in the restrained condition participants resorted to using visuospatial techniques to perform the rotations due to the lack of motor information available and therefore were less affected by the uncomfortable rotations than when unrestrained. This finding would therefore suggest that when actions are unavailable for use, visual techniques are implemented instead. However as this effect is not consistent across all rotations, caution needs to be taken when interpreting this result. The implications of this will be discussed further in the main discussion.

The results indicate a significant effect of Rotation on response times, with significantly longer response times towards rotations furthest away from the test hand orientation. This finding supports previous research into mental rotations which show a linear relationship between the rotation degrees and response times up to 180°, with significantly longer response times towards those rotations around 180° compared to those closer to the 0/360° rotations (Shepard and Metzler, 1971). This suggests that the mental rotations performed conformed to the same biomechanical constraints as when performing the action physically, suggesting a strong relationship between the mental processes employed during the planning and performing of motor actions such as these. The results also showed a significant effect of hand presentation on response times, with significantly faster responses towards unmirrored hands compared to mirrored hands. This finding supports previous research into this area, which suggests that mirrored stimuli take longer to transform as they require a full rotation in order to determine whether they are the same or not, whereas rotation times towards unmirrored stimuli are relative to their rotational angle (Shepard & Meltzer, 1971). These findings suggests that mental rotation is taking place but the lack of significant interaction between restriction and hand presentation suggests that preventing a hand movement from being physically performed does not significantly affect mental transformations of hand stimuli.

The results of the current study suggest that restricting hand movements does not significantly influence the ability to perform mental rotations of hand stimuli; however it is possible that the results found in this study could be the result of the type of stimuli used. The hand stimuli used was rotated along the frontal plane, consistent with the previous object-based rotation tasks, however it is possible that the judgements required for the task could be performed using visuospatial rather than motor techniques. As this task involved comparing two hand stimuli, using comparable hand posture stimuli may have resulted in participants using a visual matching technique in order to make accurate judgements, rather than implementing motor rotations. To determine whether this is the case, this study was replicated using both frontal and sagittal plane hand stimuli in order to investigate whether restricting compatible movements disrupts mental rotations of hand stimuli when the stimuli are not visually exact.

4.2 Experiment 5b: Mental rotation of un-matching hands

4.2.1 Introduction

The aim of Experiment 5b was to determine whether the lack of effect of restriction on rotation ability in the previous study was the result of directly comparable stimuli evoking a visuospatial rather than motor based rotation technique. In the previous study, both stimuli were presented in a frontal position therefore it is possible that judgements were made using visuospatial comparison techniques rather than implementing motor activations. In the current study, the two stimuli are presented in a frontal plane and sagittal plane orientation in order to prevent visual techniques being readily implemented to perform the task and instead encourage motor imagery techniques. Again, it is predicted that restricting hand movements will significantly affect the speed and accuracy of mental rotations of hand stimuli, with significantly longer response times and greater error rates in the restricted condition compared to when participants are unrestricted.

4.2.2 Method

Participants

A total of thirty participants took part in this study. Paid participants were recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. It was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms and back, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. Again, as foot responses were required for the entire experiment, it was specified that participants must have full mobility in their feet and wear appropriate footwear on the day to avoid any performance issues.

Materials

Stimuli

The same stimuli set, response mechanisms, restriction method and computer program were used from the previous experiment, however in the current study the test hand was presented in a frontal position with its palm facing downwards and the target hand was rotated along the Sagittal plane in 45 degrees° increments, starting at 0°. Examples of the stimuli are shown in Figure 4.6.

Figure 4.6*: Stimuli used in Experiment 5b with (l to r) non-mirrored and mirrored trials*

Design and procedure

The design and procedure is identical to that in Experiment 5a. Participants were unable to see their hands for the entirety of the experiment.

4.1.3 Results

Four participants were removed from the analysis because their error rate exceeded 10%. Error responses and RTs more than 2SDs from the participant's condition means were excluded from the analysis (total 13.69% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type

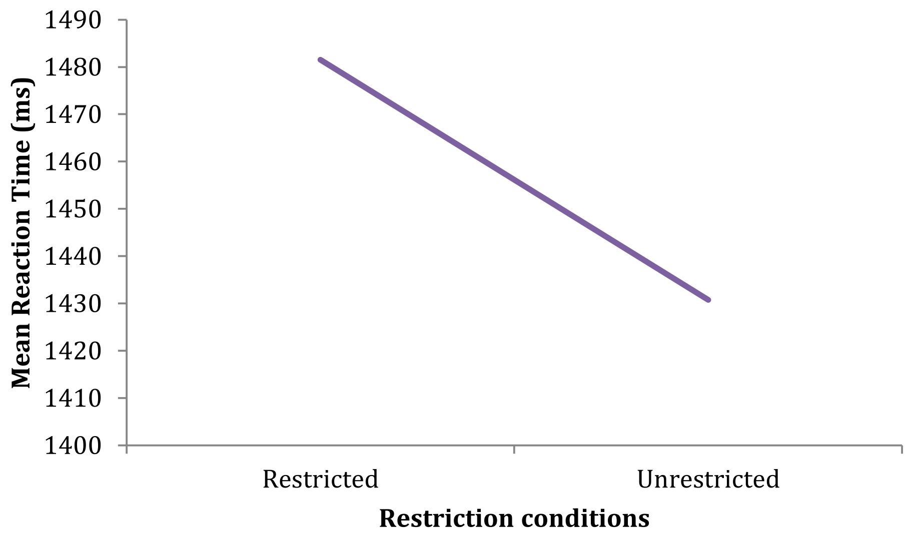


Figure 4.7. *Mean Response Times (in ms) by Restriction Condition*

(restricted/unrestricted), Hand presentation (mirrored/non mirrored) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°).

Main effects

The analysis revealed main effects of Hand presentation and Rotation on response times. Responses in the mirrored condition (M=1536ms) were significantly slower than responses in the non-mirrored condition (M=1375ms), F(1,25)=43.519, p<0.001, η_p^2 =0.635. The main effect of rotation found that RTs were significantly faster in the degrees closest to the aperture (0/360°, 45°, 270°, 315°) compared to those furthest away (90°, 135°, 180°, 225°, °), F(7,175)=31.764, p<0.001, η_p^2 =0.560. There was no significant effect of Restriction on RTs, F(1,25)=1.476, p=0.236, η_p^2 =0.056. (**R- M=**1481.551ms, **SD=**671.45/ **UR-M=**1430.775, **SD=**656.49, Figure 4.7).

Figure 4.8. *Mean number of errors by Restriction Condition*

Interactions

There was no significant interaction between Restriction and Presentation, F(1,25)=1.879, p=0.183, η_p^2 =0.070, Restriction and Rotation, F(7,175)=0.494, p=0.838, η_p^2 =0.019, or Presentation and Rotation, F(7,175)=1.121, p=0.352, η_p^2 =0.043. There was no significant three-way interaction between Restriction type, Presentation and Rotation, F(7,175)=0.763, p=0.619, η_p^2 =0.030.

Error analysis

An ANOVA was performed on the mean error score data with within-participant factors of Restriction type (restricted/unrestricted), Hand presentation (mirrored/unmirrored) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The analysis found main effects of Presentation and Rotation on error rates. The main effect of Hand presentation found that there were significantly more errors made in the Unmirrored condition (M=15.547) compared to in the mirrored condition (M=11.849), F(1,29)=7.486, p=0.011, η_p^2 =0.205. The main effect of Rotation found that significantly more errors were made towards objects rotated furthest away from the test hand (90°, 135°, 180°, 225°) compared to those closer to it (0/360°, 45°, 270°, 315°), $F(7,203)=9.628$, $p<0.001$, $\eta_p^2=0.249$. There was no main effect of Restriction on error rates, $F(1,29)=0.108$, $p=0.745$, $\eta_p^2=0.004$ (**R- M=**13.490, **SD=**13.84/ **UR- M=**13.906, **SD=**14.72, Figure 4.8).

Interactions

There was no significant interactions between Restriction and Presentation, $F(1,25)=2.894$, $p=0.100$, $\eta_p^2=0.091$ Restriction and Rotation, $F(7,203)=1.053$, $p=0.395$, $\eta_p^2 = 0.035$, or Presentation and Rotation, $F(7,203)=0.516$, $p=0.822$, $\eta_p^2=0.017$. There was no significant three-way interaction between Restriction, Presentation and Rotation, $F(7,203)=0.654$, $p=0.711$, $\eta_p^2=0.022$.

4.1.4 Discussion

The aim of this study was to investigate whether restricting the ability to perform physical hand rotations affects performance of mental rotations of hand stimuli when the stimuli themselves are not visually exact. In the previous study, the test and target hands were visually identical making it possible for judgements to be performed on a purely visual level. In order to control for this, in the current study the stimuli varied between each other with test stimuli presented in a frontal orientation and target hands rotated along a sagittal plane. The results of this study showed that there was no significant effect of restriction on restriction times and no significant interaction between restriction and any other the other experimental conditions, which suggests that restricting the participants ability to perform a physical hand rotation had no significant effect on mental rotation ability of hand stimuli.

Again the results indicate a significant effect of Rotation on response times, with significantly longer response times towards rotations furthest away from the test hand orientation. The results also showed a significant effect of Hand

Presentation on response times, with significantly faster responses towards unmirrored hands compared to mirrored hands, which is in line with previous research in this area. Both of these findings suggest that mental rotation techniques are taking place, however a lack of a significant interactions between restriction, rotation and presentation suggests that restricting physical movement in the hands does not significantly disturb mental transformations of hand stimuli as previously predicted.

In these studies, participants were required to judge whether two hand stimuli rotated at different angles were the same or different. In order to accomplish this, research suggests that participants are required to mentally transform the target hand by performing a mental rotation. The results of these two studies suggest that this is indeed occurring, however it is possible that participants are treating the target object as a visual stimulus and not recruiting motor techniques in order to perform the rotation. In the Ganis et al (2000) study, participants were explicitly instructed to imagine rotating their own hands in order to perform the rotation of the target stimulus. As a result, the left primary motor cortex activations that were found in that study could be indicative of the imagery that the participants were told to perform. If this is the case, then it is possible that in the first instance participants perform the rotations visually and only evoke motor techniques when explicitly instructed to do so. Indeed, Ganis et al (2000) suggested that motor representations are only employed at least 400ms after the beginning of each trial, before which participants rely on visuospatial techniques to perform the rotations. This therefore suggests that mental rotations of body parts can be conducted without activating the motor cortex and may provide an explanation as to the lack of significant effect of restriction found in these studies. The implications of this will be discussed further in the Discussion chapter.

The paradigm used in this study differed from that typically used for hand rotation studies and it is therefore possible that motor activations did not occur to the same level during this task. The next study investigated the effect of action restriction on mental rotation when performing the standard hand laterality judgement task (HLJT), which is typically used to investigate the mental rotation of hand stimuli. The HLJT has been shown to evoke motor activations during performance suggesting that motor techniques are actively used during this study, therefore if action availability is required for accurate performance of mental rotations of hand it should be evident in the following study.

4.2 Experiment 6a: Mental rotation of hands using laterality judgements

4.2.1 Introduction

The aim of Experiment 6a was to determine whether the lack of significant main effect of restriction found in the previous study was due to participants using Visuo-spatial techniques to perform the mental rotations rather than motor-based techniques. In the previous study, participants were required to judge whether two hands rotated at differing angles from each other were the same or different. It is possible that as no explicit instructions were provided to participants to use motor techniques to make their judgement, participants treated the hands as purely visual stimulus' and therefore didn't imagine a transformation of their own body part in order to make a judgement. This next study aimed to examine this by using the hand laterality judgement task paradigm. Research into this paradigm suggests that laterality judgements require sensorimotor simulations of egocentric movement in order to complete accurately, with individuals actively imagining the transformation of their own hand into line with that of the stimulus in order to make the judgement (Parsons, Gabrieli, Phelps & Gazzaniger, 1998). Research has also shown that individuals can experience kinaesthetic sensations during laterality tasks, especially for those stimuli in uncomfortable or biomechanically impossible positions, suggesting that mental representations of the stimuli are accessed in order to perform the rotations (Parsons, 1994). Based on previous research, the use of a laterality judgement task in the following experiment should encourage mental simulation of the rotation movement and subsequently result in motor activations. It was predicted that restriction of hand movements during the hand laterality judgement task should lead to an update of the body schema and incorporation of the unavailability of actions into the simulation, resulting in longer reaction times and more errors in the restricted conditions compared to in the unrestricted conditions.

4.2.2 Method

Participants

A total of thirty participants took part in this study. Paid participants were recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. It was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms and back, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. It was specified that participants must have full mobility in their feet and wear appropriate footwear on the day to avoid any performance issues.

Materials

The same stimuli set was used as in the previous experiment, however in Experiment 6a participants were presented with only one image per trial and were required to judge its laterality. Hands were rotated along a median plane, with 0/360° indicating an upright position. Examples of the stimuli used are shown in Figure 4.9.

Restriction

The same restriction methods were used from the previous experiment.

Design and Procedure

The design and procedure is identical to that in Experiment 5, however participants were required to respond according to whether the test hand was either left or right, with a right foot response for right hands and a left foot response

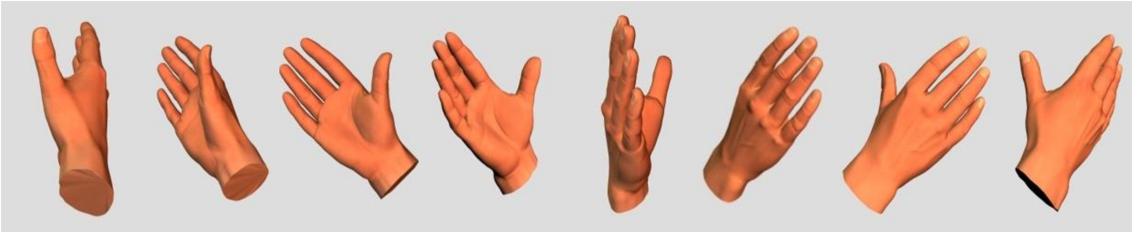


Figure 4.9: *Stimuli used in Experiment 6a- Right hand rotated (l to r) 0°/360° to 315°*

for left hands. Participants were unable to see their hands for the entirety of the experiment.

4.2.3 Results

Five participants were removed from the analysis because their error rate exceeded 10%. Error responses and RTs more than 2SDs from the participant's condition means were excluded from the analysis (total 16.66% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted/unrestricted), Hand laterality (left/right) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) (See Appendix 3 for full analysis)..

Main effects

The analysis revealed significant main effect of Rotation on response times. Responses were significantly faster in the degrees closest to the aperture (0/360°, 315°) compared to those furthest away (45°, 90°, 135°, 180°, 225°, 270°, 315°), $F(7,168)=39.845$, $p<0.001$, η_p^2 =0.624. There were no significant main effects of Restriction type, $F(1,24)=0.922$, $p=0.346$, η_p^2 =0.037 (**R- M=**1019.808ms, **SD=**549.93/ **UR- M=**999.654, **SD=**553.96, Figure 4.10) or Hand Laterality, $F(1,24)=3.305$, $p=0.082$, η_p^2 = 0.121, on Response Times.

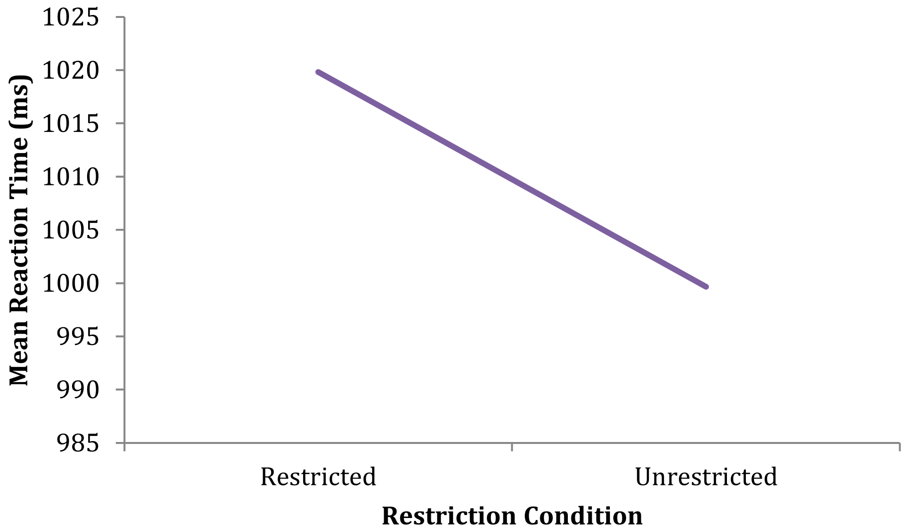


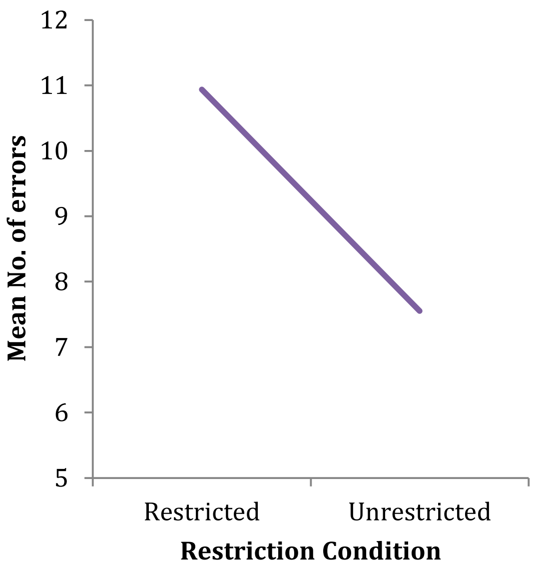
Figure 4.10: *Mean Response Time (in ms) by Restriction condition*

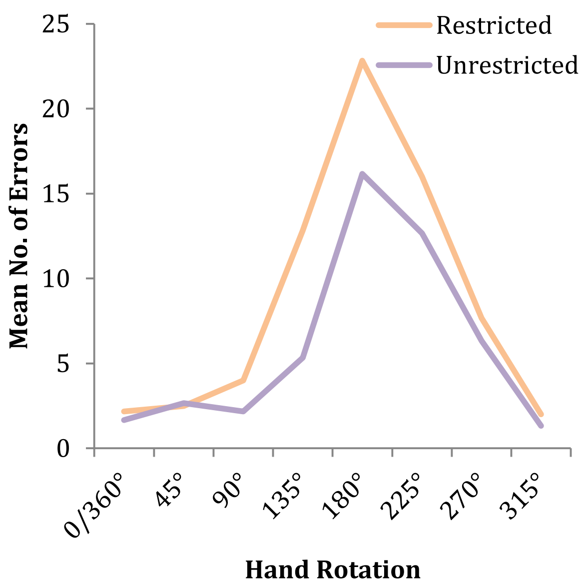
Interactions

There was no significant interaction between Restriction type and Hand Laterality, F(1,24)=0.396, p=0.535, η_p^2 =0.016, Restriction Type and Rotation, F(7,168)=1.392, p=0.212, η_p^2 =0.055 or Hand Laterality and Rotation, F(7,168)=0.949, p=0.470, η_p^2 =0.038. There was no significant three-way interaction between Restriction type, Hand presentation and Rotation, F(7,168)=1.184, p=0.315, η_p^2 =0.047.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean error score data with within-participant factors of Restriction type (restricted/unrestricted), Hand Laterality (left/right) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The analysis found main effects of Restriction and Rotation on error rates. The main effect of Restriction found that there were significantly more errors made in the Restricted condition (M=10.938, SD=11.52) compared to in the unrestricted condition (M=7.552, SD=8.59), F(1,29)=8.595, p=0.007, η_p^2 =0.229 (Figure 4.11). The main effect of Rotation found that significantly more errors were made towards





(L) Figure 4.11: *Mean number of errors by Restriction Condition*

(R) Figure 4.12: *Mean Number of Errors for Experiment 6a by Object Presentation and Restriction*

objects rotated furthest away from the aperture (135°, 180°, 225°, 270°) compared to those closer to it (0/360°, 45°, 90°, 315°), F(7,203)=21.690, p<0.001, η_p^2 =0.428. There was no main effect of Hand Laterality on error rates, F(1,29)=0.040, p=0.843, η_p^2 =0.001.

Interactions

The interaction between Restriction type and Rotation was significant, F(7,203)=3.191, p=0.003, η_p^2 =0.099, with more errors towards rotations around the 180° rotation in the restricted condition compared to in the unrestricted condition, (Figure 4.12). Post hoc comparisons using the Fisher LSD revealed that that were significant differences between response times at the 135° (p=0.005) and 180 ° (p=0.022) rotations across restriction conditions but no significant differences between the other rotation angles across restriction conditions (p>0.05). There were no significant interactions between Restriction type and Hand Laterality, F(1,29)=2.257, p=0.144, η_p^2 =0.072 or Hand Laterality and Rotation, F(7,203)=0.123, p=0.997, η_p^2 =0.004. There was no significant three-way interaction between Restriction type, Hand Laterality and Object Rotation, F(7.203)=1.202, p=0.303, η_p^2 =0.040.

4.2.4 Discussion

The aim of this study was to determine whether restricting hand movements and making them unavailable for action effects participants' ability to perform mental rotations of hand stimuli during the hand laterality judgement task. In this study, participants were presented with an image of a hand rotated at varying degrees along the sagittal plane and were required to judge whether the hand was a left or right hand whilst their hands were physically restrained to prevent movement. The results of this study found that there was no significant main effect of restriction on reaction times during the mental rotations, which suggests that restricting hand movement does not interfere with participants' ability to perform the laterality tasks. The laterality task was used in this study because previous research has demonstrated that active egocentric motor imagery techniques are used to complete the task, however the lack of effect of restriction indicates that unavailability of movement does not disrupt participants ability at performing simulations of the rotation movement. Again the results were consistent with previous mental rotation studies and showed a significant effect of rotation angle on reaction times, with longer reaction times towards larger and physically awkward orientations. This suggests that mental rotation is occurring but the lack of interaction between restriction and rotation suggests that restricting participants hand movements does not prevent them from being able to perform a mental simulation of the rotation of hand stimuli.

The results did indicate that restriction had a significant effect on error rates, with significantly more errors in the restricted condition compared to in the unrestricted condition. This finding is in line with our prediction that restriction would result in more errors in the restricted conditions as making the physical movement unavailable disrupted participants ability at performing the simulation. However, the lack of significant effect of restriction on reaction times suggests that when restricted participants were still able to perform the rotations at the same speed but with greater error rates compared to in unrestricted conditions. This could suggest that the ability to perform an action is not necessary for the performance of a mental rotation of a body part, however the ability to integrate information stored in the structural body schema with visual information is significantly impaired, resulting in greater errors when restricted. This has important implications for this thesis and will be discussed in greater detail in the Discussion.

The significant interaction between restriction and rotation on error rates indicated that participants made significantly more errors in the physically uncomfortable rotations in the restricted condition compared to in the unrestricted condition which suggests that restriction significantly disrupted simulation ability in the rotations that were not represented in the mental representation of the hand. Research has shown that in order to perform the simulation of hand rotation, participants access the mental representation of the hand which contains motor information regarding previous movements, along with information provided by the body schema regarding current capabilities of the limb (Cooper & Shepard, 1975). Information regarding movements of biomechanically impossible rotations will not be included in the representation; therefore individuals will have to rely on other mechanisms to perform a simulation of those movements. Research into the mental simulation ability of amputees has shown that individuals who have lost an arm are still capable of performing mental rotations of hand stimuli, with increased response times to unnatural rotations, but are less accurate due to a disruption to the performance of the neural networks controlling the simulation (Nico et al, 2004). This finding is similar to the results found in this experiment, which showed that motor imagery was still occurring in restricted conditions but error rates were significantly higher, especially towards unnatural rotations. Nico et al (2000) suggest that in amputee patients the mental representation still exists, along with motor information regarding the structural constraints of the body part, but information regarding the current positioning of the limb is obviously unavailable making simulation impaired. As a consequence of this, amputees employ visual-spatial techniques in these situations resulting in higher levels of inaccuracy. The similarity between the finding of this study and the results of the present experiment suggest that restricting actions in this experiment may have led to similar cognitive effects, with participants relying on visual-spatial techniques in the higher rotation angles rather than simulation. In unrestricted conditions, participants will be able to predict what a visual image of the uncomfortable positions will look like by accessing motor information contained in the mental representation and integrating this with the visual information provided in the stimuli. However, in the restricted conditions the prevention of movement may affect participants' ability to predict the visual image of uncomfortable orientations using previous motor information, resulting in higher error rates in the restricted condition, especially towards uncomfortable and impossible orientations. This finding suggests that in this study the restriction of hand movements did not significantly influence the speed of rotation of correct responses but it did influence participants' ability to integrate motor and visual information to predict the laterality of stimuli, resulting in greater errors in restricted conditions, especially towards uncomfortable orientation stimuli. This suggests that when foot responses are required for response, restricting hand movements disrupts our ability to make accurate hand laterality judgements but not rotation ability in general.

In this study, participants responded using foot presses, however research into the mental rotation of body parts has shown that performance of a motor action during a mental rotation task can influence mental rotation ability (Wolschlager & Wolschlager, 1998). In order to account for any interference effects that may have occurred during this study, the study was replicated with voice responses used instead of foot responses, in order to determine whether restriction effects rotation of hand stimuli when no limb responses are required.

4.3 Experiment 6b- Mental rotation of hands using laterality judgements and voice responses

4.3.1 Introduction

The aim of this study was to determine whether restriction of hand responses influences mental rotation ability of hand stimuli during the hand laterality judgement task when no overt movement is required for responses. In the previous experiments, participants responded with their feet however research into mental rotation suggests that performance of a motor action during a mental rotation task can influence mental rotation ability. Research by Wolschlager and Wolschlager (1998) found that when participants were performing a motor rotation task alongside a mental rotation task, the dynamics of the motor task interfered with mental rotation ability, with faster mental rotations when accompanied by faster motor rotations and vice versa. This finding suggests that motor actions performed alongside mental actions can have a significant effect on motor imagery. Although participants weren't performing a motor rotation task alongside the HLJT, it is possible that the use of foot responses interfered with the restriction technique by focussing motor attention onto the foot as opposed to the hands, therefore in this experiment participants responded with verbal responses to determine whether restriction has an effect of mental rotation when no limb responses were used. Based on previous research, it was predicted that when participants hands are restricted, simulation of the rotation task will be disrupted, resulting in longer response times and significantly more errors in the restricted condition.

4.3.2 Method

Participants

A total of thirty participants took part in this study. Plymouth University students participated as part of a course requirement for a compulsory module in

Research Methods. Paid participants were also recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. It was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. It was also specified at recruitment that participants must speak English as their first language, to prevent any language effects.

Materials

The same stimuli set were used from the previous experiment. The responses in this study were made verbally, therefore responses were recorded using a voice response device developed by Herga Electric Limited, which was connected to a parallel port. The box has an inbuilt microphone and responses were recorded from the onset of the word. The voice box recorded that a response had been made and actual responses were recorded manually. The responses were standardized across participants, with a "right" verbal response for right hand and a "left" verbal response for a left hand.

Restriction

The same restriction methods were used from the previous experiment.

Design and Procedure

The design and procedure is identical to that in Experiment 6a, however responses were made verbally. Again, participants were unable to see their hands for the entirety of the experiment.

4.3.3 Results

Six Participants were removed from the analysis because their error rate exceeded 10%. Error responses and RTs more than 2SDs from the participant's

Figure 4.13: *Mean Response Time (in ms) by Restriction condition*

condition means were excluded from the analysis (total 20% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (restricted/unrestricted), Hand presentation (left/right) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°).

Main effects

The analysis revealed main effects of Hand Laterality and Rotation on response times. Responses towards right hands (M=1057ms) were significantly faster than responses towards left hands (M=1168ms), $F(1,23)=16.239$, $p=0.001$, η_p^2 =0.414. The main effect of rotation found that RTs were significantly faster in the degrees closest to 0/360° (45°, 90°, 315°) compared to those furthest away (135°, 180°, 225°,270°), $F(7,161)=27.488$, $p<0.001$, η_p^2 =0.544. There was no significant effect of Restriction on RTs, $F(1,23)=0.018$, $p=0.895$, η_p^2 =0.001 (**R- M=**1110.946ms, **SD=**502.22/ **UR- M=**1115.148, **SD=**537.57, Figure 4.13).

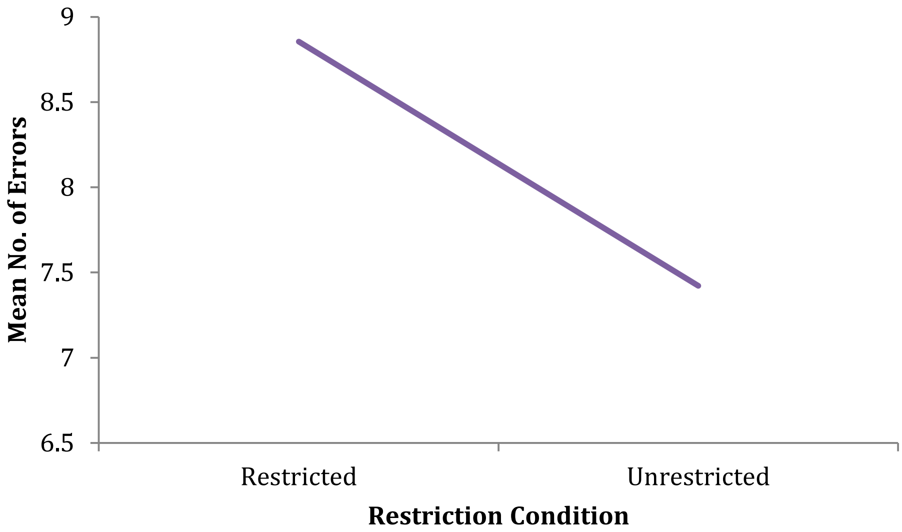


Figure 4.14: *Mean Number of Errors by Restriction condition*

Interactions

There was no significant interaction between Restriction and Laterality, F(1,23)=1.609, p=0.217, η_p^2 =0.065, Restriction and Rotation, F(7,161)=1.052, p=0.397, η_p^2 =0.044 or Hand Laterality and Rotation, F(7,161)=1.346, p=0.232, η_p^2 =0.055. There was no significant three-way interaction between Restriction, Laterality and Rotation, F(7,161)=1.088, p=0.374, η_p^2 =0.045.

Error analysis

An Analysis of Variance (ANOVA) was performed on the mean error score data with within-participant factors of Restriction (restricted/unrestricted), Hand Laterality (left/right) and Rotation (0/360°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The analysis found a main effect of Rotation on error rates, with significantly more errors made towards objects rotated furthest away 0/360° (135°, 180°, 225°, 270°) compared to those closer to it (45°, 90°, 315°), F(7,203)=11.896, p<0.001, η_p^2 =0.291. There were no main effects of Restriction type, F(1,29)=1.575, p=0.219, η_p^2 =0.052 **(R- M=**8.854, **SD=**13.97/ **UR- M=**7.422, **SD=**10.08, Figure 4.14) or Hand Laterality, F(1,29)=0.040, p=0.844, η_p^2 =0.001 on error rates.

Interactions

There were no significant interactions between Restriction and Hand Laterality, F(1,29)=0.162, p=0.690, η_p^2 =0.006, Restriction and Rotation, F(7,203)=0.514, p=0.824, η_p^2 =0.17 or Hand Laterality and Rotation, F(7,203)=0.853, p=0.545, η_p^2 =0.029. There was no significant three-way interaction between Restriction, Hand Laterality and Object Rotation, F(7,203)=1.217, p=0.295, η_p^2 =040.

4.3.4 Discussion

The aim of this study was to investigate whether restricting participants' ability to move their hands disrupted their ability to perform a hand laterality judgement task of rotated hand stimuli when voice responses are required for a response. The results of this study found that there were no significant effects of restriction on correct response times, which suggests that restriction of hand movements doesn't interfere with participants' ability to perform mental rotations of hand stimuli. Again, the results indicated a significant effect of rotation on reaction times, with significantly longer response times towards uncomfortable rotations compared to more comfortable rotations. This suggests that participants were performing mental simulations of physical rotations that abide by the constraints posited by physical movements. However, the lack of significant interaction between restriction and rotation suggests that restriction of hand movements did not disrupt participants' ability at performing simulations of the rotation.

Analysis of error rates was consistent with previous mental rotation research with significantly more errors towards objects rotated in physically uncomfortable rotations. However, there was no significant interaction between restriction and rotation on error rates; therefore participants were able to perform the rotations with the same speed and accuracy when restricted as when unrestricted. This finding is in conflict with the results found in the previous experiment, which could therefore suggest that the increased error responses in the restricted condition in the previous study could be a direct result of response conflict as the result of using foot responses. The overall findings of this study therefore suggest that restricting hand movement did not significantly influence participants' ability to judge the laterality of hands and subsequently perform simulations of a hand rotation task.

4.3.4 General Discussion

The aim of these studies was to determine whether restricting participants' ability to perform physical hand rotations significantly affects their ability to mentally simulate such actions during a hand rotation task. In these experiments, participants were presented with 3D images of hands rotated at varying degrees and were required to make a judgement regarding whether two hands were the same or different (Experiment 5a & 5b) or regarding the laterality of one hand (Experiments 6a & 6b). In order to accurately do this, research suggests that the individuals will mentally simulate a rotation of their own hands in order to bring them into line with the test stimuli. Research has shown that motor processes are heavily involved in the mental rotations of body parts, with the same activations found during mental rotations as when performing the action physically (Ganis et al, 2000). Research has also shown that mental simulations conform to the same structural constraints and capabilities as physical actions, suggesting that the same processes are used for both the mental simulation and physical performance of actions (Cooper & Shepard, 1975). As a consequence of this, if the simulations abide by the same performance rules as physical enactment of those actions, restriction of hand actions should be incorporated into any motor imagery resulting in a disruption to the simulation process. This should therefore result in significant differences in response times and error rates between restricted and unrestricted conditions.

It was predicted that temporarily preventing movement in the arms and hands of participants would significantly affect their ability to perform mental rotations of hand stimuli as the body schema should incorporate the incapacity into any subsequent mental simulations, resulting in a disturbance in mental rotation ability. The lack of significant effect of restriction in all four studies suggests that individuals are capable of performing mental simulations of actions even when that action is not available for performance; therefore the ability to physically perform an action at that moment in time is not a requirement for successful simulation of actions. This finding suggests that in order to perform a simulation, information regarding the general capabilities of that particular limb is accessed and incorporated into the simulation, not "of-the-moment" capabilities. This will be discussed further in the Discussion chapter.

Previous research into the cognitive processes involved in the mental rotation of hands has shown that changing the current posture of participants' hands has a significant effect on mental rotation times, with longer rotation times when current hand posture is not compatible with the position of the hand stimuli. For instance, the mental rotation time of hand stimuli increases significantly when participants' hand are behind their back compared to when resting on their knees in front of them (Ionta et al, 2007). This suggests that the current posture of our hands is incorporated into the body schema and influences subsequent performance of simulations of the motor action. In the current studies, participants' posture remained the same in both restricted and unrestricted conditions and the results indicated no significant difference in response times between restricted and unrestricted conditions. This indicates therefore that the increased response times found in previous studies can be attributed to the change in posture rather than the unavailability of action information, as the results of the current studies demonstrate that information regarding current physical capabilities is not required for accurate simulation of actions. It can therefore be concluded that in order to perform a simulation of a hand rotation, the most essential information required is the current positioning of the limb as it is this that the starting point of the simulation is based on.

The results of the experiments in this series suggest that restricting hand movements did not interfere with participants' ability to perform mental rotations of hand stimuli. However, research suggests that this could be due to a transferring of representations used to perform the rotations. Ganis et al(2000) suggested that when participants are required to perform mental rotations of feet stimuli, mental representations of hands may be accessed instead to perform the mental rotations. They suggest that as hands and feet are biologically similar in both their biomechanical constraints and their appearance, it is possible that when information regarding the foot representation is unavailable, the image of a foot can be transferred onto the mental representation of the hand and that can be used instead as a replacement. If this is the case, then it is also possible that the reverse can occur when the representation of a hand is not available. When participants were restricted, access to the mental representation of the hand may have been disturbed therefore participants may have accessed the mental representation of the foot instead and used this information in order to perform the mental rotations. As the posture of the hands remained the same throughout the experiment, participants would have been able to use information regarding the current posture of the hand to initiate the simulation; therefore performance would be the same as if unrestrained. This transferability of representations could therefore provide an explanation for the lack of significant effect of restriction found in these studies and also demonstrates the plasticity of mental representations themselves.

In conclusion the results of these studies suggest that restricting hand movements did not have a significant effect on participants' ability to perform mental rotations of hand stimuli, therefore individuals need not be currently capable of performing that action in order to be able to perform a mental simulation of the action. The implications of this finding will be discussed more in the Discussion chapter. All of the previous experiments so far have required participants to make action based or structural judgements of static stimuli, such as tools, abstract objects and hand stimuli, and have shown no effect of restriction on participants' ability to perform these judgements. The final series of experiments aims to look at the effect of restriction when participants are required to make judgements based on active action performance of other individuals, specifically time to contact judgements of an active reaching action.

Chapter 5- Exploring the relationship between action understanding and movement ability

Introduction

The previous experiments in this thesis have focused on the effect of restriction on the mental simulation of movements when making judgements of static objects or stimuli. The mental simulations that occur are in these tasks are dependent on the observations of the objects themselves, rather than on observation of an action. The results of these studies showed no significant effect of restriction on performance in these tasks, which suggests that the simulations required to accurately make these judgements are not influenced by the current availability of actions. The final series of studies aims to investigate whether restricting reaching movements in participants has a significant effect on the ability to simulate the observed movement of another individual.

Action observation has been extensively studied in recent years leading to the discovery of mirror neurons in the brain that automatically fire upon observation of a motor action (Gallese et al, 1996). Mirror neurons have been found to respond upon observation of another individual performing an action within one's repertoire, resulting in the activation of the corresponding motor action. This activation leads to the potentiation of that action, resulting in faster performance when subsequently required (Gallese et al, 1996- See Chapter 1 for a review of mirror neuron research). Explanations of this activation can be found in Simulation research. When we encounter an action being performed, we access its mental representation which enables us to use previous performance of that action in order to predict what is likely to occur in this setting. Simulation research suggests that accessing the mental representation leads to the activation of motor codes associated with that action, resulting in the performance of a mental simulation of the action. This simulation process not only enables us to understand the situation but also predict what is likely to occur based on previous experience (Ambrosini et al, 2011).

The current series of experiments aims to look at the effect of action restriction on participants' ability to judge the reaching actions of others. In these studies, participants observed another individual reaching towards an object and were required to predict when they will come into contact with that object, without actually seeing the contact at any point during the experiment. As a result, research suggests that the participants will mentally simulate the reaching movement in order to accurately judge the point of contact (Ambrosini et al, 2011). In this study, the speed of reaching was manipulated therefore participants will have to incorporate the speed of movement into their simulation in order to make an accurate judgment.

The paradigm for this series of studies is based on Craighero and Zorzi's (2012) study into the effect of action restriction and object-grasp compatibility on participants' ability to make accurate time to contact judgements. In their study, participants watched the experimenter reach towards an object with either a compatible or incompatible grasp size and were required to judge when they thought the experimenter would come into contact with the object using either a hand or foot response. The video contained the entire movement from lift-off to contact with the object and participants performed half of the experiment with their hands bound. The results found that when the grasp size was congruent with the object, time to contact judgements were significantly more accurate than when the grasp size was incongruent. Research into canonical neurons has shown that when individuals observe an object, the motor areas associated with physical interaction with it are automatically activated, resulting in increased readiness to perform that action (Craighero et al, 2008). Priming research has also shown that the priming of an action facilitates the subsequent detection of compatible objects, therefore participants should, after visually processing the target object, be able to predict the correct hand action required for interaction with it, resulting in facilitated responses when the hand shape and object are congruent. Craighero et al (2008) results only indicated a facilitation effect between compatible grasps and objects when the hands were free to move. This finding suggests that when the hands were available for action, the perception of a grasping action led to the mental simulation of that reaching action and the perception of the object enabled access to the mental representation of the object, resulting in activation of the appropriate responses required for interaction with that object. The subsequent visuomotor and motor priming effects resulted in the increased accuracy of judgements towards compatible action/object pairings found in the unbound hand condition.

The results also indicated an interaction between response type and restriction on response accuracy. They found that when participants responded with their hands, their responses were more accurate when their hands were unbound but foot responses were more accurate when hands were bound. The authors suggest that when the hands were bound, the lack of available action resulted in the dissipation of the visuomotor and the motor priming effects typically found in these studies. They suggest that a hand unable to perform any actions cannot be primed for action by the observation of a grasping movement which results in the higher levels of inaccuracy shown when responding with hands during the restricted condition, despite previous activations of this action through the observation of an object. When the hands were bound and foot responses were used, however, the activation was transferred to foot resulting in the more accurate responses in this condition (Craighero & Zorzi, 2012).

The results of Craighero and Zorzi' s (2012) studies suggest that when participants observed the reaching actions, the inability to perform a compatible action significantly disrupted participants ability to integrate the visual information contained in the scene with the motor information communicated by the actions. The aim of this current series of research aims to look at the effect restricting an action has on our ability to perceive that action being performed in another individual. In this final series of experiments, participants watched an individual reaching towards a number of different objects; however participants never see the individual come into physical contact with the object. The speed of reach movement varied throughout the experiment and participants were required to judge when they predict the individual would come into contact with the object if they continued moving with the same speed. If the ability to move is essential for the accurate observation of other people's actions, then restriction of a reaching action should significantly influence the accuracy of participants' judgements. If this finding occurs, then it can be concluded that the ability to perform an action is essential for accurate understanding of the behaviours of others.

In the previous studies in this thesis, the main movements being simulated by observation of the objects were hand movements; therefore hand movement was the primary action being restricted. In the current study, the action most likely to be potentiated by the videos is that of a reaching movement, therefore reaching movements needed to be restricted. In order to do this, participants performed half of the experiment with their hands held behind their back. Previous studies investigating restriction on motor simulation have typically used restriction techniques that involve tying or twisting participants' hands behind their back, however this can not only restrict the action but also substantially change the posture of the hands and arms. In order to avoid hand posture rather than action restriction influencing the results of this study, participants held their hands behind their back without twisting them to ensure that a reaching action was sufficiently restricted without manipulating the natural posture of the arms.

5.1 Experiment 7a: Time-to-Contact Judgements of reaching movements

5.1.1 Introduction

The aim of this study is to investigate whether restricting reaching ability in participants has a significant effect on their ability to predict the speed of reaching movements of others. In this study, participants observed a video of an individual reaching towards an object and were required to predict when the individual would come into contact with the object. Unlike in Craighero and Zorzi' s (2012) study, participants don't see the individual come into contact with the object, therefore in order to accurately predict when the contact will occur participants will be required to actively simulate the reaching movement performed by the individual. In this study, the speed of reaching movement varied between trials therefore in order to make an accurate time to contact judgement participants will need to incorporate this speed into their simulation.

Previous research suggests that in order to perform the simulation, participants are required to access the mental representation of the movement which contains sensory and motor information regarding previous performances. This information should then be combined with information from the body schema which informs the individual of their current physical capabilities. In the present study, the restriction of a reaching movement should be incorporated into the simulations; therefore restricting participants reaching ability should result in them being unable to accurately mentally simulate the speed of reaching movements performed by the actor, resulting in a flat lining of response times across the three speeds in the restricted conditions.

In this study, the videos were created using 10 frames of images, with the speed of reaching manipulated by varying the timings of frame presentation from 50ms per frame, 75ms per frame and 100ms per frame. The 75ms speed is consistent with a "normal" grasping speed, with 50ms and 100ms being noticeable faster and slower than the normal reach speed. In this study, participants do not see the actor come into contact with the object at any point, therefore it would be very difficult for them to be able to accurately judge when the contact would be, regardless of whether they are restricted or not. Accuracy of simulation was instead judged on the participants' ability to represent the differing speeds of reaching within their simulations, therefore accurate simulations should represent the 50ms speed condition being significantly faster than the 75ms condition, which should in turn be significantly faster than the 100ms speed condition. It is therefore predicted that when participants are unrestricted, there should be a significant difference in the time to contact responses across the three speed conditions, with responses in the 50ms speed condition significantly faster than responses in the 75ms and 100ms conditions. However when participants are restricted, these differences should disappear as a result of the disruption to the simulation of the reaching action. In line with this, it is predicted that the 50ms should be most affected by the restriction method due to the vast contrast between the restricted movement ability and the movement being observed on screen.

Exclusively right handed individuals were recruited for this study, as is consistent with previous research in this area in order to investigate the effect of restriction on the simulation of actions performed using the dominant hand(Craighero & Zorzi, 2012). Mental representations of movements contain information regarding previous performance of these movements; therefore in right handed individuals, right handed movements should be increasingly represented than left handed movements as it is these that are typically performed by a right handed individual. Based on previous research, it is predicted that right handed individuals should be able to simulate right handed movements with increased accuracy compared to left handed movements therefore it is predicted that there should be a significant interaction between reach direction and speed on response times, with significantly more accurate responses towards right handed reaches compared to left handed reaches (Craighero & Zorzim 2012). When participants are restricted, the disruption to the simulation should remove the dominant hand reach advantage contained in the mental representation. If these effects are found it can be concluded that current ability to perform an action is required to be able to predict and understand the actions of others.

5.1.2 Method

Participants

A total of thirty Psychology undergraduates from Plymouth University participated in this study as part of a course requirement for a compulsory module in Research Methods. Right handed participants were recruited for this study, as is consistent with previous research in this area (Craighero & Zorzi, 2012). It was specified at the recruitment stage that all participants must have normal to corrected vision as they were required to view visual stimuli as part of the experiment. It was also requested at recruitment that participants must have full mobility in their arms and back, with no history of any chronic pain, strokes or immobility conditions such as arthritis. As foot responses were required for the entire experiment, it was specified that participants must have full mobility in their feet and wear appropriate footwear on the day to avoid any performance issues.

Materials

Stimuli

Videos of reaching movements towards household objects were used in this experiment. The videos consisted of an actor reaching towards a familiar household object situated in front of them with either a left or right diagonal reach, with left reaches performed with the individual's left hand and vice versa. The videos were developed using MovieDek ® and consisted of 10 frames, each representing a progression in movement. Each frame measured 960 x 540 pixels in dimension with a black background of 1024 x 768 pixels. The objects used were; apple, beer, bottle opener, chocolate bar, can, packet of crisps, hairbrush, pen, scissors, screwdriver, and toothbrush. An example of a typical frame is shown in Figure 5.1. Hand shape is held consistent throughout the reaches to prevent the forming of a hand shape from providing information to the participant regarding the distance from the object. The timings between frames varied from 50ms, 75ms, and 100ms. Only one speed condition was used per trial and each object was presented equally with a left and right handed reach for each Reach speed condition.

The experiment was developed using the Slide Generator 2007.3.3 program developed by Dr Mike Tucker of the University of Plymouth. It was performed on a Samsung Sync Master 2043 computer screen, with a screen resolution of 1680 x 1050 with 32bt colour quality. Responses were made using foot pedals developed by Herga Electric Limited connected to a parallel port. Only one response was required for this study therefore participants responded exclusively with their right foot.

Figure 5.1 : *Example of a typical frame with (L-r) left reach and right reach to a bottle opener.*

Restriction

Participants performed half of the experiment with their hands held behind their back. The order of restriction was balanced between participants, with half performing the first portion of the experiment under restriction and half performing it freely. This was to ensure that restriction order did not influence the results.

Design and Procedure

A within subjects design was used in which each participant was exposed to all conditions. Participants were seated at individual desks with a computer screen and the foot response pedals on the floor with the appropriate foot resting on the response pad. The chair was adjusted for individual comfort to enable comfortable manipulation of the foot pedals. Participants were informed prior to the experiment in both the brief and verbally that some restriction techniques would take place and were shown images replicating the restriction methods employed. The experimenter was present at all times during the procedure to ensure that the participants remained within the restraints and for safety reasons.

Each participant was required to perform 5 practice trials with the option of repeating this phase prior to the test trials. Successful completion of the practice phase was required before the experiment could begin. The videos were presented individually on the screen and participants were required to respond at the moment they believe the individual in the video would come into contact with the object if they had continued along the same speed and trajectory with the appropriate foot response. There were three conditions in this experiment: Restriction type (restricted or not restricted), Reach direction (right or left) and Reach Speed (50ms, 75ms, 100ms). Restriction condition was blocked but Reach direction and Reach Speed was randomised between slides.

Each trial began with the appearance of a black screen for 500ms to indicate that the trial was about to begin. The video was then presented which was followed by the presentation of a black scene, during which participants were required to respond. Each trial ended when a participant responded or 5000ms had elapsed. A black screen was then displayed for 500ms before the beginning of the next trial. The sequence of stimuli presentation was randomised for each participant.

5.1.3 Results

Reaction times more than 2SDs from the participant's condition means were excluded from the analysis. One participant was removed from the analysis as more than 10% of their results were excluded from the analysis (total 4.1% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An ANOVA was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (Restricted/Unrestricted), Reach direction (left/right) and Reach Speed (50/75/100ms) (See Appendix 4 for full analysis).

Main effects

There were significant main effects of Reach direction and Reach Speed on reaction times. Responses towards Left reaches (reaches towards the left of the screen-

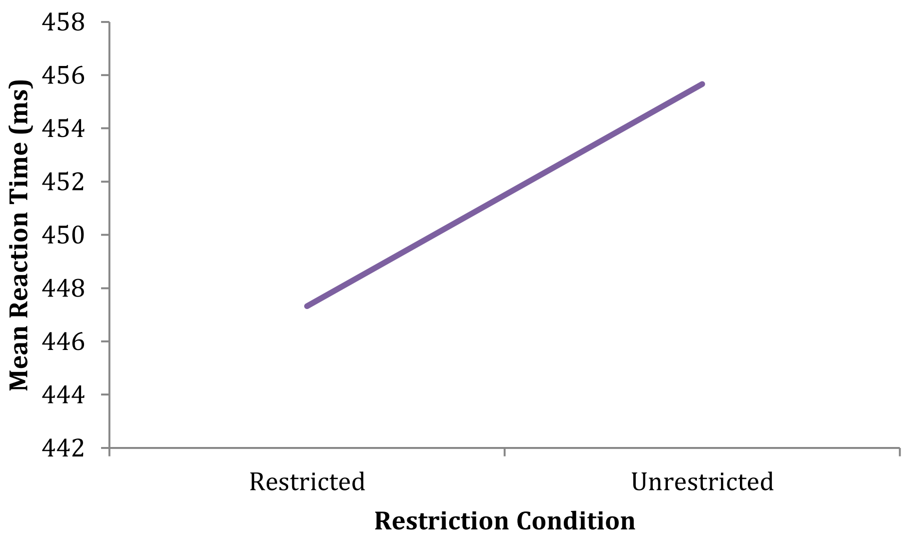


Figure 5.2*: Mean Reaction times (in ms) by Restriction condition*

M=444.838 ms) were significantly faster than right reaches (reaches towards the right of the screen- M=460.156ms), F(1,28)=8.021, p=0.008, η_p^2 =0.223. The main effect of Reach Speed found that there were significant differences between response times in the three speed conditions of 50ms (M=425ms) 75ms (M=441ms) and 100ms (M=487ms), F(2, 56)=5.596, p=0.023, η_p^2 =0.167. Pairwise comparisons between the three speed conditions indicated a significant difference between the three speeds at the 0.05 level. The main effect of restriction was not significant, F(1,28)=0.198,p=0.660, η_p^2 =0.007 (**R- M=**447.327, **SD=**337.58/ **UR- M=**455.666, **SD=**335.45 , Figure 5.2).

Interactions

There was a significant interaction between Restriction type and Reach Speed, F(2,56)=6.542, p=0.003, η_p^2 =0.189, (Figure 5.3). Post hoc comparisons using the Fisher LSD revealed that that were no significant differences between response times across restriction conditions at Timing 1 (50ms, p=0.264),

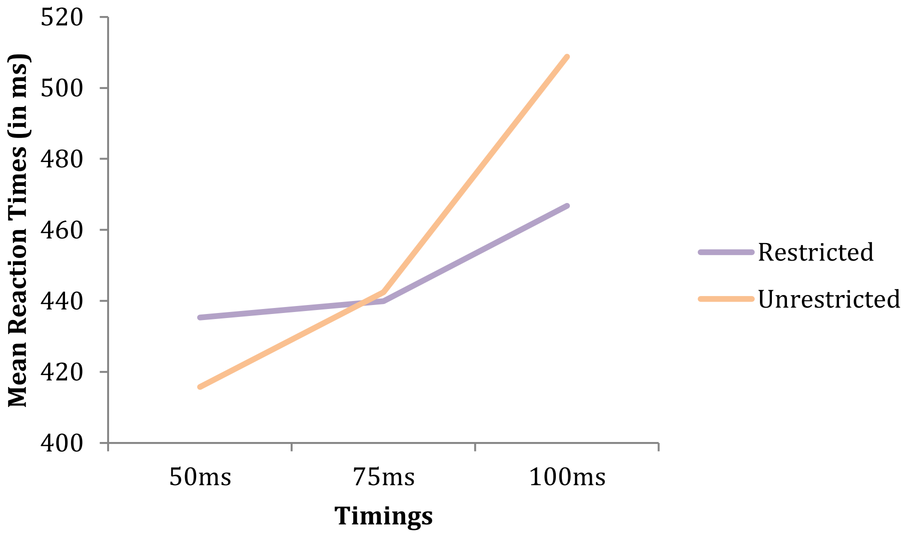


Figure 5.3*: Mean reaction times in Experiment 7a by Reach Speed and Restriction*

Timing 2 (75ms, p=0.884) or Timing 3 (100ms, p=0.123). Further post hoc comparisons also revealed that there were no significant differences between responses across the three timing conditions when participants were restricted (p>0.05) but there were significant differences in response times between Timing 1 (50ms) and Timing 2 (75ms, p=0.005),Timing 1 and Timing 3 (100ms, p=0.06) and between Timing 2 and Timing 3 (p=0.022) in the unrestricted condition. There were no significant interactions between Restriction and Reach direction , F(1,28)=1.404, p=0.246, η_p^2 =0.048 and Reach direction and Reach Speed, F(2,56)=1.988, p=0.146, η_p^2 =0.066, and no significant three-way interaction between Restriction type, Reach direction and Reach Speed, F(2,56)=0.148, p=0.862, η_p^2 =0.005.

5.1.4 Discussion

The aim of this study was to determine whether restricting participants' ability to perform a reaching movement significantly affects their ability to make an accurate time to contact judgement when observing another individual perform the action. In this study participants responded using their feet according to when they predicted that the individual in the video would make contact with the object if they continued moving at the same speed. The results of this study indicated a significant interaction between Restriction type and Reach Speed, with a linear increase in response times between the three speed conditions in the unrestricted condition but little variation between response times in the three speed conditions in the restricted condition. This finding suggests that when individuals were free to move, participants were able to accurately simulate the action parameters of the observed movement resulting in accurate representations of the different speeds of reach in the response times. When participants were unable to move, however, the restriction was represented in the simulation resulting in participants being unable to accurately simulate the movement speeds as performed by the individual. This finding is in line with the predictions made for this study and provides support for the theory that the ability to perform an action is directly linked to the ability to make accurate judgements of others actions.

The results indicated significant main effects of reach direction on response times, with significantly faster responses towards left reaches compared to right reaches. This could be the result of the handedness of the participants. In order to control for possible confounding effects of handedness on the perception of reaches, exclusively right-handed participants were recruited for this study, which is consistent with previous studies in this area (Craighero & Zorzi, 2012). When these participants access the mental representation of the reaching movement, they will have stronger activations for a right handed reach compared to a left handed reach as this will be their dominant action. In the current study, participants observed another individual reaching towards an object from the view of them being sat opposite them. As a result, reaches towards an object in the left portion of the screen were performed using the individual's left hand but corresponded to the participant's right hand. As a result, these movements would be represented with increased strength in the participants' mental representation of the movement, resulting in reduced response times towards these stimuli. The results indicate however that there was no interaction between Restriction and Reach direction, and no three way interaction between Restriction type, Reach direction and Reach Speed, therefore restricting participants ability to perform a reaching action does not disrupt the ability to retrieve certain action based information from the mental representation of the reaching movement.

The results of the current study suggest that restricting participants' ability to perform a reaching action significantly disrupted their ability to make accurate speed judgements of a reaching movement performed by another individual, which suggests that the ability to perform an action is required to understand another person's actions at that moment in time. In the present study, the actions performed by the individual primed a hand/reaching action but participants performed the responses with their feet. Research suggests that when an object primes a hand action, responses will be significantly faster and more accurate when a hand response is made as a result of the motor resonance communicated by the object. This coupled with the reaching movement performed by the actor should facilitate the performance of hand responses in this experiment. Craighero and Zorzi (2012) found a difference in response patterns between restricted and unrestricted conditions when participants responded with feet and hands, suggesting that the effect of restriction on the understanding of behaviours can be moderated according to the type of response made. In order to determine whether the effect of restriction on simulation differs when the responding limb corresponds with that represented by the movement, Experiment 7b was replicated with the use of hand responses in replacement of the foot responses in this study.

5.2 Experiment 7b: Time-to-Contact Judgements of reaching movements - Hand Response

5.2.1 Introduction

In the previous study, participants observed an actor reaching towards an object and were required to respond when they predicted the actor would come into contact with the object. According to previous research, the observation of a reaching action in this study should result in the activation of the brain areas associated with performance of that action, facilitating performance of that response when subsequently required. In the previous study, participants responded using a foot response; however research suggests that as hand responses are potentiated by both the observation of the object and action, these responses should be most susceptible to the disruptive effects of restriction on simulation ability (Craighero & Zorzi, 2012). In Craighero and Zorzi's (2012) study, participants were primed to perform a particular hand movement through both the observation of the object and observation of the grasping movement. The results indicated that hand responses were significantly affected by the restriction of actions, even though performance of the response was not affected by the restriction, with significantly more accurate responses towards compatible object/reach combinations when unrestricted but a disappearance of this advantage when responses were bound. The opposite effect was found when responses were made using the feet instead. Craighero and Zorzi (2012) suggest that responses in the hand condition were particularly susceptible to the effect of restriction as a hand action was primed through both the object and the reach action, resulting in facilitated responses when hands were free but inhibited responses when hands were restrained. The aim of the current experiment is therefore to investigate the effect of action restriction on the active simulation of a reaching movement when hand responses are required.

Based on the results of the previous experiment, it is again predicted that restricting a reaching action should have a significant effect on participants ability to judge the speed of movement of the actor, represented by a relative flat lining of response times in the restricted condition across all speed conditions but a significant difference between judgements in the three speed conditions when unrestricted. It is also predicted that there will be an overall significant difference between response times in the restricted and unrestricted conditions. This is due to the facilitation of a hand action in this study communicated by both the object and reaching action. When participants are unrestricted, their responses should be significantly faster overall as this action will be potentiated by the stimuli, however when restricted responses should be significantly slower as restriction should disrupt the action information communicated by both the object and reach. If this effect is found, then it can be concluded that the availability of action performance is a determining factor in our ability to understand the movements of other people.

5.2.2 Method

Participants

A total of thirty Psychology undergraduates from Plymouth University participated in this study as part of a course requirement for a compulsory module in Research Methods. Right handed participants were recruited for this study. It was specified at the recruitment stage that all participants must have normal to corrected vision due to the fact that they were required to view visual stimuli as part of the experiment. It was also requested at recruitment that participants must have full mobility in their arms and back, with no history of any chronic pain, strokes or immobility conditions.

Materials

The same stimuli set were used from the previous experiment. The responses in this study were made using finger response devices developed by Herga Electric Limited connected to a parallel port. The devices were held between the participant's fore finger and thumb in the participants' dominant hand in both restriction conditions.

Restriction

The same restriction methods were used from the previous experiment.

Design and Procedure

The design and procedure is identical to that in Experiment 7a, however responses were made using finger button devices.

5.2.3 Results

Reaction times more than 2SDs from the participant's condition means were excluded from the analysis (total 0.6% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An Analysis of Variance (ANOVA) was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (Restricted/Unrestricted), Reach direction (left/right) and Reach Speed (50/75/100ms).

Main effects

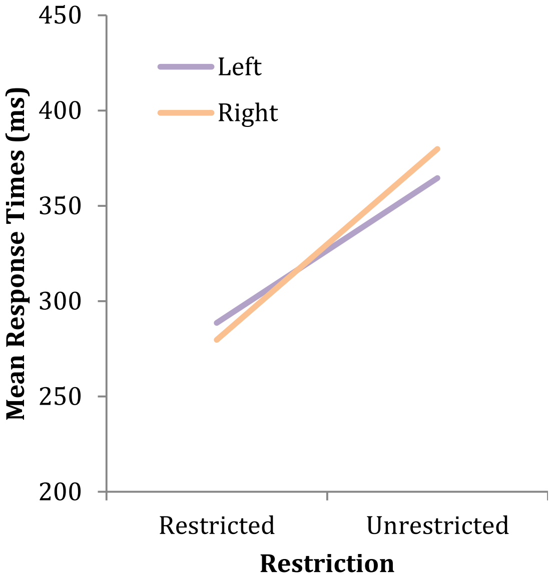
There were significant main effects of Restriction type, Reach direction and Reach Speed on Reaction Times. Responses in the Restricted condition (M=278.630ms, SD= 90.34) were significantly faster than responses in the Unrestricted condition

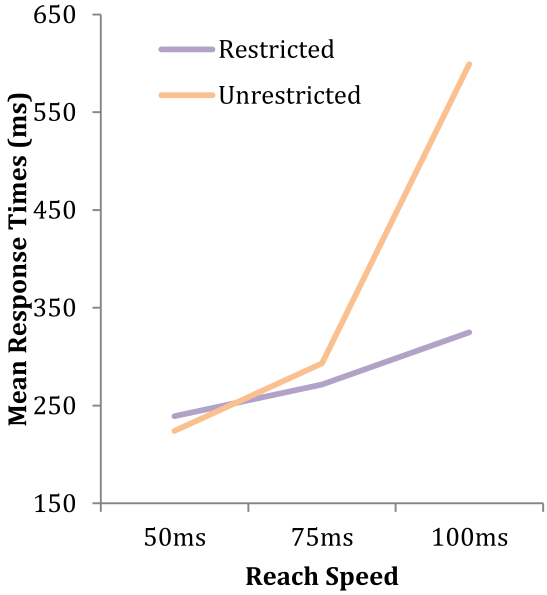
Figure 5.4*: Mean Response Times for Experiment 7b by Restriction condition*

(M=372.217ms, SD= 215.75), F(1,29)=84.596, p<0.001, η_p^2 =0.745 (Figure 5.4). The main effect of Reach direction indicated that responses in the Left Reach condition (M=321.108ms) were performed significantly faster than responses in the Right Reach condition (M=329.740ms), F(1,29)=4.396, p=0.045, η_p^2 =0.132. The main effect of Reach Speed also demonstrated a significant difference between the speeds, with the responses in the 50ms speed condition (M=231ms) significantly faster than responses in the 75ms (M=282ms) and 100ms (462ms) conditions, F(2,58)=352.696, p<0.001, η_p^2 =0.924. Pairwise comparisons between the three speed conditions indicated a significant difference between the three speeds at the 0.05 level.

Interactions

There were significant interactions between Restriction type and Reach direction, F(1,29)=5.373, p=0.028, η_p^2 = 0.132, with faster responses towards left handed reaches in the restricted condition and faster responses towards right handed reaches in the unrestricted condition(Figure 5.5). Post hoc comparisons





(L) Figure 5.5*: Mean Response Times for Experiment 7b by Restriction and Reach Direction*

(R) Figure 5.6: *Mean Response Times for Experiment 7b by Reach Speed and Restriction*

using the Fisher LSD revealed that that were significant differences at the $p<0.001$ significance level between response times across restriction conditions towards both left and right reaches. There was also a significant interaction between Restriction and Reach Speed, $F(2,58)= 134.507$, $p<0.001$, $\eta_p^2 = 0.823$ (Figure 5.6). Post hoc comparisons using the Fisher LSD revealed significant differences in reaction times at the $p<0.001$ significance level between Timing 1 (50ms), Timing 2 (75ms) and Timing 3 (100ms) across both restriction conditions. There was also a significant interaction between Reach direction and Reach Speed, $F(2,58)=8.914$, $p=0.002$, $\eta_p^2 = 0.235$ (Figure 5.7), and a significant three-way interaction between Restriction , Reach Direction and Reach Speed, $F(2,58)=7.625$, $p=0.002$, $\eta_p^2 =0.208$.

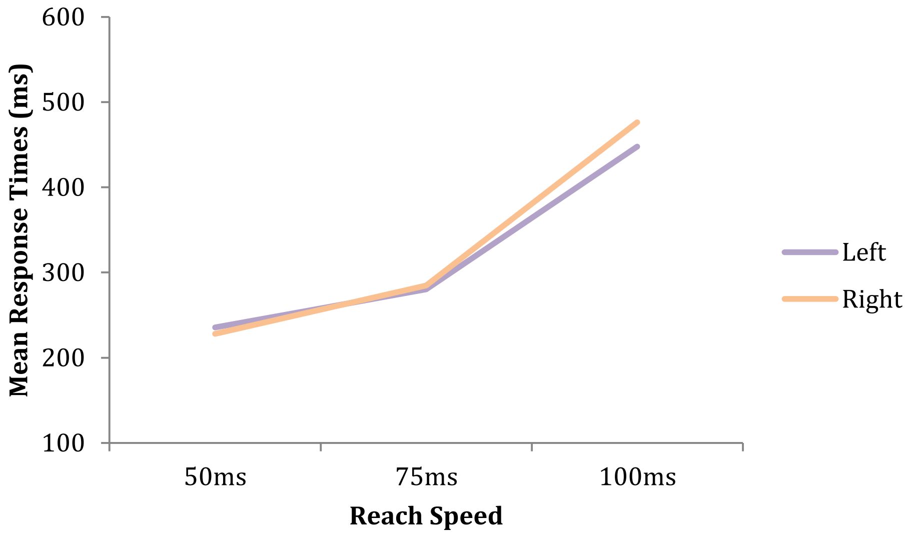


Figure 5.7*: Mean Response Times for Experiment 7b by Reach speed and Reach Direction*

5.2.4 Discussion.

The aim of this study was to determine whether restricting participants reaching ability significantly affects their ability to make an accurate time-to-contact judgement of another individuals reaching action when responses are made with their hand. Previous research suggests that hand responses are more susceptible to restriction effects than foot responses as these actions are afforded by the reaching action and therefore restriction should significantly disrupt the simulation of these actions. The results of this study again indicate a significant interaction between Restriction and Reach Speed, with the results in the direction predicted. The results of this analysis indicated that responses in the restricted condition increased linearly as speed increased, which suggests that participants were able to process that the speeds were different, but were unable to accurately represent this in their reaction times (239ms, 271ms and 324ms respectively). Responses in the unrestricted condition also increased linearly as speed increased, however response times for the 100ms speed were double those for the 50ms speed which indicates that in the unrestricted condition, participants were able to represent the differences in speed of reach across the 50ms and 100ms speed conditions and represent this in the simulations. This finding was consistent with the results of the previous experiment and suggests that restricting participants' ability to perform a reaching action significantly impaired their ability to simulate and predict the speed of another individual's movements. This will be discussed further in the Discussion chapter.

The results demonstrated a significant main effect of restriction type on response times, with faster responses when participants were restricted compared to unrestricted. This finding was in the opposite direction to that predicted, as previous research suggested that responses in the unrestricted condition should be faster than when restricted as the hand response is potentiated by both the object and the action, thereby facilitating responses in the unrestricted condition (Craighero & Zorzi, 2012). A possible explanation for this result could be due to the effect of the restriction on the simulation of the reaching speeds observed by the participants. Based on previous research, restricting a reaching movement should disrupt participants ability to simulate the movements performed by the actor by removing the motor priming effect communicated by the reaching action, which should subsequently inhibit the accurate processing of reach speed (Craighero & Zorzi, 2012). The results of this study indicate that when reaching actions were restrained, participants were unable to accurately simulate the reaching movements performed by the actors and consequentially were unable to accurately represent the speed of the reaches in their simulation. As a result of this, participants in the restrained condition perceived all reaches to be performed at a similar rate. However, although a reaching action was inhibited through the restriction, a hand action was not therefore hand responses would still have been potentiated through processing of the target object resulting in facilitated hand responses and consequentially a low overall response time mean. In the unrestricted condition, participants responses were representative of the differing speed conditions resulting in significant differences in response times across the three speed conditions, with reaches in the 100ms condition judged to be twice as long as 50ms reaches which is representative of the true difference in movement speeds as performed by the actors. As a consequence, these response times varied accordingly resulting in higher overall responses in the unrestricted condition compared to the restricted condition. It is worth mentioning, however, that responses towards the 75ms speed reaches do not lie neatly in the middle of these two points, which suggests that although participants were able to judge the relative difference between the slowest and fastest speeds, this was not as easily done for the middle speed. A possible explanation for this could be that the 75ms speed was most representative of a real life, natural movement and therefore participants have more experience of performing a movement like this in their everyday lives. As a result of this, participants might be more able to actively represent this speed over the other speed conditions by accessing information contained in their mental representation of this action. In the 50ms and 100ms conditions, the reaches were noticeably faster and slower respectively than a normal speed movement and are less likely to be experienced by participants to the same extent as the 75ms speed reaches. As a result of this, participants may have under or overestimated their responses resulting in significantly faster and slower, but potentially less accurate, response times. It is impossible in the current study to make any assumptions regarding the accuracy of responses however it would be interesting in future studies to investigate this to determine whether this is indeed the case as this would provide further evidence for the mental representation of movements.

Again, the results indicated a significant effect of reach direction on response times, with reaches to the left being judged as quicker than those towards the right. This finding can be explained by the ease of simulating a movement involving the dominant hand compared to a non-dominant hand. The significant interaction between restriction type and reach direction, however, shows that there is no difference between response times in the two reach conditions when participants are restricted but there is a difference when participants are unrestricted. This is a very interesting finding and suggests that when participants are restrained, the advantage of performing a simulated movement involving the dominant hand over the non-dominant hand is removed as there is no reaching action available to be primed, resulting in a lack of motor priming usually found in these types of reaching actions (Craighero & Zorzi, 2012). When participants are making their time to contact judgements, they will access the mental representation of the reaching movement in order to mentally simulate the action as accurately as possible based on previous interactions. These mental representations will typically represent the action from both handedness orientations but superiority will be given to the dominant hand, resulting in faster simulation and execution of these actions as a result of familiarity of movement. When the corresponding motor action is unavailable to be performed, however, there will be no advantage of performing a judgement of a dominant hand associated action as the simulation will incorporate the incapacity into it despite the activation of the action codes associated with that movement. This finding therefore suggests that restricting a reaching action disrupts the retrieval of previous action information from the mental representation, thereby removing the dominant hand advantage.

The results of the current study suggest that restricting participants' ability to perform a reaching movement significantly influences their ability to make accurate time to contact judgements of a reaching action performed by another individual. These findings were particularly influenced by the performance of a hand action rather than a foot response. The findings suggest that the restriction of a reaching action prevented participants from being able to accurately simulate the reaching action of another and were subsequently unable to accurately represent the speed of that reaching movement within their simulations. This therefore supports the theory that the ability to perform an action significantly influences our ability to understand and accurately represent the action of another.

Research suggests that observation of a motor action leads to the automatic activation of mirror neurons which in turn leads to the activation of the motor codes associated with that movement; therefore the observation of a reaching movement should lead to activation of the hand and arm motor areas, resulted in facilitated responses when made using these effectors. However, mirror neuron research suggests the existence of two different types of mirror neurons- those that activate when the action being observed matches identically with that coded by the neuron and those that fire when action matches the goal action contained within the mental representation (Gallese et al, 1996). As a consequence of this finding, mental representations of actions do not only code the action but also the goal of that action, therefore facilitation affects can occur when different affecters are used to perform the action. The results of the previous two studies indicate that a facilitation effect as a result of action observation is occurring when responses are made with both hands and feet, as demonstrated by the interaction between Restriction type and Reach Speed found in both studies, which provides support for the theory that mirror neurons code actions according to the goal, not necessarily the movement made. It is possible that the facilitation effects demonstrated in the previous two studies occurs due to the functional similarity between feet and hands as responders, therefore the final study in this series used verbal responses to determine whether the motor facilitation effect still occurs when no physical actions are required for response and a verbal response is made instead.

5.3 Experiment 7c- Time-to-Contact Judgements of reaching actions - Voice Response

5.3.1 Introduction

The final experiment in this series aims to determine whether restricting reaching ability significantly affects participants' ability to accurately judge the time of contact of another person's reach when verbal responses are used. The results of the previous two studies have shown a significant interaction between restriction and reach times on time to reach judgements when responses are made with both feet and hands. This finding supports previous research into this area and suggests that activations can be transferred when an action is unavailable for performance, as demonstrated in the foot response experiment. The final experiment in this series aims to investigate whether the facilitation effect demonstrated in the previous experiments is found when no physical response is required. Previous mirror neuron research suggests that the facilitation effects demonstrated in the previous experiments should dissipate when verbal responses are made as the observation of the reaching action should not prime verbal responses (Craighero & Zorzi, 2012). As a result, restriction should have no significant effect on response times when a verbal response is required. However, simulation research suggests that verbal responses are still affected by the motor facilitation affect when simulations are taking place as demonstrated in mental rotation studies in this thesis. In order to investigate this, the previous experiments were replicated with voice responses used to signal when participants believed the contact to take place. Based on previous research, it is predicted that restriction of a reaching movement should significantly affect participants ability to make point of contact judgements when observing another individuals movements, however the results should be less significant than when responses are made using foot or hand responses.

5.3.2 Method

Participants

A total of thirty participants took part in this study. Plymouth University students participated as part of a course requirement for a compulsory module in Research Methods. Paid participants were also recruited via the Plymouth University School of Psychology paid participant pool and took part in this study for payment of £4. Right handed participants were recruited for this study. It was specified at the recruitment stage that all participants must have normal to corrected vision and full mobility in their arms, with no history of any chronic pain or strokes or immobility conditions, such as arthritis or dystonia. It was also specified at recruitment that participants must speak English as their first language, to prevent any language effects.

Materials

The same stimuli set were used from the previous experiment. Verbal responses were used in this experiment; responses were recorded using a voice response device developed by Herga Electric Limited, which was connected to a parallel port. The box has an inbuilt microphone and responses were recorded from the onset of the word. The voice box recorded that a response had been made and actual responses were recorded manually. The responses were standardized across participants, with a "now" verbal response to indicate when participants think contact will be made.

Restriction

The same restriction methods were used from the previous experiment.

Design and Procedure

The design and procedure is identical to that in Experiment 7a & b, however responses were made verbally.

5.3.3 Results

Reaction times more than 2SDs from the participant's condition means were excluded from the analysis. One participant was removed from the analysis as more than 10% of their results were excluded from the analysis (total 6.79% of responses removed from the analysis). The mean reaction times for each condition were computed for each participant. An ANOVA was performed on the correct reaction times (RTs) with within-participant factors of Restriction type (Restricted/Unrestricted), Reach direction (left/right) and Reach Speed (50/75/100ms).

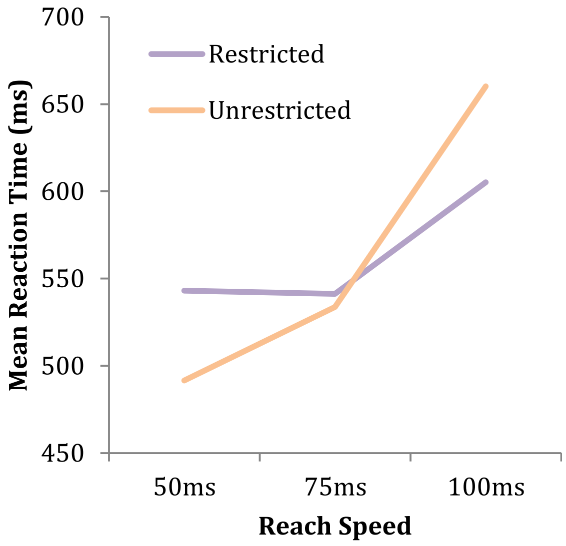
Main effects

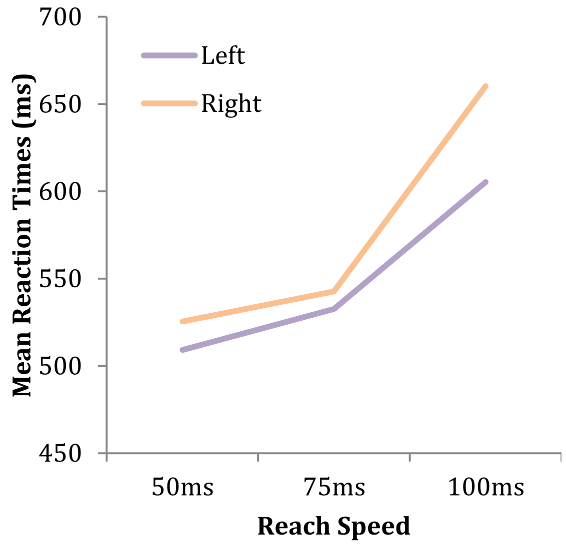
There were significant main effects of Reach direction and Reach Speed on reaction times. Responses towards Left reaches (reaches towards the left of the screen using a right hand- M=548.943 ms) were significantly faster than right reaches (reaches towards the left of the screen using a left hand- M=576.08ms), F(1,28)=7.040, p=0.013, η_p^2 =0.201. The main effect of Reach Speed found that there were significant differences between response times in the three Speed conditions of 50ms (M=517.296) 75ms (M=537.558ms) and 100ms (M=632.680ms), F(2, 56)=34.447, p<0.001, η_p^2 =0.552. Pairwise comparisons between the three speed conditions indicated a significant difference between the three speeds at the 0.05 level. The main effect of Restriction was not significant, F(1,28)=0.005,p=0.943, η_p^2 =0.000 (**R- M=**563.196, **SD=**347.38/ **UR- M=**561.827, SD=305.39, Figure 5.8).

Figure 5.8: *Mean Response Times in Experiment 7c by Restriction condition*

Interactions

There was a significant interaction between Restriction type and Reach Speed, F(2,56)=8.182, p<0.001, η_p^2 =0.226 (Figure 5.9). Post hoc comparisons using the Fisher LSD revealed that that were no significant differences between response times at Timing 1 (50ms) and Timing 2(75ms) when restricted(p=0.781) but significant differences between Timing 1 and Timing 3 (100ms, p=0.001) when restricted and significant differences between response times at Timing 1 and Timing 2 (p=0.004), Timing 1 and Timing 3 (p<0.001) and Timing 2 and Timing 3 (p<0.001) when unrestricted. There was also a significant interaction between Reach direction and Reach Speed, F(2,56)=5.084, p=0.009, η_p^2 =0.154 (Figure 5.10) . There was no significant interaction between Restriction type and Reach direction, F(1,28)=0.445, p=0.510, η_p^2 =0.016, and no significant three way interaction between Restriction type, Reach direction and Reach Speed, F(2,56)=0.971, p=0.385, η_p^2 =0.034.





(L) Figure 5.9*: Mean Response Times in Experiment 7c by Reach Speed and Restriction*

(R) Figure 5.10: *Mean Response times in Experiment 7c by Reach Speed and Reach Direction*

5.3.4 Discussion

The aim of this experiment was to determine whether restricting a reaching movement significantly affected participants ability to make time to contact judgements of another individuals reaching movement when verbal responses are required. The results of this study again found a significant main effect of Reach speed on responses, with significant differences in response times towards the three speed conditions. The response times increased linearly across the reach speed conditions, which suggest that participants were able to accurately represent the differing speeds in their simulations. The results also indicated a significant interaction between Restriction and Reach Speed, with differences between response times across the three speed conditions when unrestricted and little variability between response times towards speeds 1(50ms) and 2 (75ms) but increased response times towards speed 3 (100ms) in the restricted condition. This finding suggests that even when participants were restricted, they were still able to accurately represent the differing speed of the 100ms reaches compared to the other reach speeds, as represented by the increased response times towards these reaches. This suggests that restricting motor actions did not completely disrupt the ability to accurately mentally simulate the observed actions when voice responses were required. Previous research into the motor facilitation effect suggests that responses should only be facilitated when responses are made using the effector afforded by the action, in the case of this study hand responses. The results of this study suggest that when verbal responses are required, the restriction of a reaching movement does prevent participants from being able to simulate the parameters of the reaching action as accurately as when unrestricted, however they are still able to accurately represent the difference in speed between the slowest and fastest Reach speeds. Again, there was a significant main effect of Reach direction on response times, with significantly faster responses towards left reaches performed with a right hand. The lack of significant interaction between Restriction and Reach direction, however, suggests that the advantage that dominant hand representation has over non dominant hands when performing mental simulations is still present when participants are restricted, which suggests that the restriction of a reaching action does not disrupt the ability to retrieve certain previous performance information from the mental representation when verbal responses are required.

The findings of this study suggest that restricting reaching ability in participants significantly disrupted their ability to accurately judge the time of contact of a reaching action when verbal responses were made, however participants' response indicated that the differing reach speeds were still processed as reflected by increased response times towards the 100ms speed compared to the 50ms speed. This suggests that current ability to perform an action is a determining factor of simulation accuracy; however verbal responses are not affected in the same velocity as motor responses.

General Discussion

In the current studies, participants viewed an individual reaching towards an object at varying speeds of movement and were required to predict when the individual would come into contact with the object. In order to make an accurate judgement, research suggests that the participants will mentally simulate the reaching action, taking into account speed of movement and distance from the target object as well as physical capability information provided by the body schema (Craighero & Zorzi, 2012). It was predicted that restriction of a reaching movement would disrupt participants' ability to simulate the reaching movement of the individual and therefore participants' time to contact judgements should not be representative of the differing speeds of movement in the restricted condition. If participants are able to accurately represent the speed of movements in the unrestricted condition but not in the restricted condition, it can be concluded that the ability to perform an action significantly influences our ability to understand that action when it is performed by another. The results of all three experiments in this series indicated a significant interaction between Restriction and Reach speed, with a steady linear increase between response times across the speed conditions in the unrestricted condition but little variance between responses across speeds in the unrestricted conditions. This finding suggests that when participants were unable to physically perform a reaching action, their ability to represent and simulate the dynamics of the reaching behaviour of another individual was significantly impaired.

In this series of experiments, participants observed an actor reaching towards the object but never actual contact with the object. As a consequence, participants are required to make time-to-contact judgements by mentally replicating the movement as performed by the individual, taking advantage of the performance cues in the scene that provide information regarding when contact is likely to have occurred, in this case speed of reach. Research into mirror neurons has shown that when we observe another perform performing an action, the motor areas in the brain that represent that action are activated, resulting in increased readiness to perform that action when subsequently required (Gallese et al, 1996). In the current series of experiments, observation of the action should have been sufficient to lead to an activation of the motor areas involved with performance of a reaching action, thereby potentiating performance of a reaching movement in the participants. Restricting reaching ability significantly affected participants' ability to perceive the speed of the movements, as represented in the significant interaction between restriction and time. This suggests that it is difficult to process and understand the parameters of another individual's actions when we are unable to currently perform these actions ourselves at that moment in time. Simulation research suggests that when actively simulating a movement, we access the mental representation of the action in order to inform us how to behave (Barsalou, 2008). This then leads to the activation of the associated motor codes responsible for performing this action in real life. Research has shown that simulations are bound by the same physical constraints as real actions, as often demonstrated by the mental rotation paradigm (see Chapter 4 for a review of this paradigm), which suggests that mental representations also contain information from the body schema regarding our body's physical limitations (Parsons, 1994). The results of the affordance experiments in Chapter 2 suggest that canonical neurons, the neurons that respond when an object is observed, are not influenced by action restriction and therefore Visuo-motor priming is not influenced by temporary changes to the capabilities of the body. The results of the present studies, however, suggest that mirror neurons and motor priming are influenced by changes in the body's capabilities. Mirror neurons reflect the actions of others onto the neural networks of the individual perceiving them, resulting in a mirroring behaviour which includes activation of the associated motor actions. The results of these studies suggest that the temporary unavailability of actions is also represented in the neural systems thereby disrupting the subsequent motor activations, which results in a disruption to the motor priming effect. When participants go on to perform a conscious mental simulation of the action, this disruption to the mirror neurons is reflected in the simulation and results in an inability to accurately represent the action that the mirror neurons represent. This finding has major implications regarding the mechanisms used to process other peoples actions and will be discussed further in the Discussion chapter.

In conclusion, the findings of these studies suggest that the availability of movement is a contributing factor when simulating an action performed by another individual. When participants mentally simulate the actions of another person temporary changes to the capability of the body are represented in the simulation, influencing subsequent performance or judgements of these actions. This therefore suggests that the ability to perform an action is directly related to our ability to both neurally represent and understand the actions of other people, which in turn suggests a very strong link between the body and cognition providing support for the Embodied theory of Cognition.

Chapter 6- Discussion and Conclusions

The experimental work in this thesis aimed to determine whether restricting the performance of motor actions significantly influenced our ability to perform mental simulations involving those movements. The findings of this research, including a meta-analysis, and its implications for theories of Embodied Cognition will be discussed in this chapter together with possibilities for future research. Finally, a conclusion will be made based on the overall results of this thesis regarding the relationship between the body and cognition.

6.1 Meta-analysis

A meta-analysis of the current experiments was conducted in order to determine the overall effect of restriction on reaction time across all experiments.

Method:

Cohen's d value, Standard Error, Lower and Higher limit 95% Confidence interval, Z value and p value were computed for the main effect of Restriction for all experiments, the results of which were plotted onto a forest plot and included in an omnibus. Forest plot points were weighted according to sample sizes.

Results:

The results of the meta-analysis indicate a slight shift towards an effect of restriction in experiments 4c, 1a, 5b, 2 and 6a, with longer reaction times in restriction conditions in these studies- however it is important to note that the effect size in these studies is very small therefore caution must be taken when interpreting these results. The meta-analysis also indicated a shift towards an effect of the control condition in experiments, 7a, 7b 4b, and 3b with longer reaction times in the

Exp	Cohen's *d*	SE	Lower Limit	Upper limit	Z Value	P-value
4c	0.147	0.073	-249.44	221.88	-0.196	0.422
1a	0.078	10.91	-54.43	50.02	-0.518	0.302
5b	0.076	41.8	-258.01	252.42	-0.719	0.236
2	0.053	0.357	-2.87	3.01	-0.792	0.214
6a	0.036	20.98	-215.53	217.19	-0.396	0.346
1b	0.015	19.75	-72.02	72	0.64	0.739
7c	0.004	18.87	-126.43	111.15	1.58	0.943
3a	0.004	7.495	-157.39	154.94	0.64	0.739
5a	-0.003	33.82	-223	242.06	0.178	0.571
4a	-0.003	49.64	-214.32	208.18	0.271	0.607
6b	-0.008	31.61	-200.93	215.06	1.253	0.895
7a	-0.03	0.012	-122.89	122.06	0.412	0.66
4b	-0.034	41.31	-200.49	218.21	1.058	0.855
3b	-0.103	4.414	-41.4	44.16	-0.911	0.181
7b	-0.565	10.18	-32.9	115.26	-5.999	<0.001
All	**-0.183**	**23.42**	**-99.42**	**76.63**	**-0.233**	**0.514**

Cohen's d and 95% CI

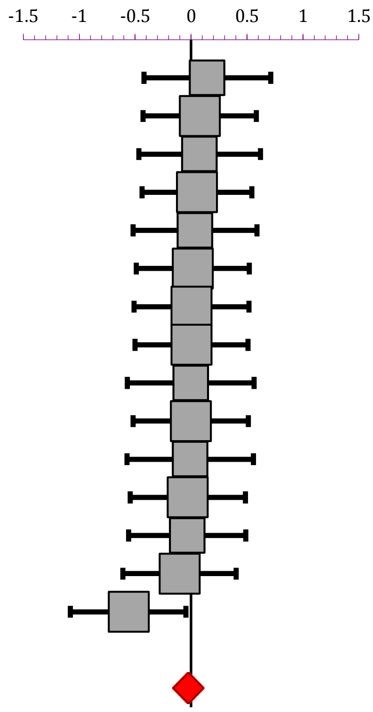


Figure 6.1: *Meta-analysis omnibus of Experiments 1a-7c*

unrestricted conditions. The remaining studies indicated no preference for either the control or intervention.

Examination of the Cohen's d figure in these studies indicates that, with the exception of studies 7b, all Cohen's d values are below +/-0.2, which indicates a very small effect size. This would suggest that there is a small difference between the means of restricted and unrestricted conditions in these studies. Experiment 7b, however, has a Cohen's d value of -0.0565, which suggests a moderate effect size. This is in conflict with the highly significant p value, which suggests that the effect of restriction is not as large as previously predicted. The combined Cohen's d score for all experiments indicates a small effect size of -0.183, which suggests that overall there is a very small effect of restriction on response times in these experiments, with slightly slower response times across all experiments when participants are restricted.

Analysis of the 95% confidence intervals indicates that the lower and higher intervals for all experiments cross the 0 point which indicates an overall non-significant effect. There is also a very large difference between the lower limit and higher limit for all experiments, except for Experiment 2, which indicates a large degree of variation in response times across participants in these studies. The combined Lower and Higher CI scores across all studies ranged from -99.42 to 76.63, which combined with the combined Standard Error of 23.42 indicates a wide range of variability across participants responses which suggests overall that the effect of restriction was not significant. This is supported by the combined p value of 0.514.

Conclusion:

The results of the meta-analysis indicate that with all studies combined responses are slightly slower in the restricted condition, however this effect is very small and not statistically significant (p=0.514). The combined results indicate a high Standard error and large variation between Lower Limit and Higher Limit CIs, which suggests a large variation between participants' responses across restriction conditions. This indicates that the effects of restriction found in these studies are accurate and represents a true non effect. The combined results support the individual experimental findings which suggest that the restriction of movement in these studies has no effect on overall response times which in turn suggests that restricting actions has no significant effect on performance speed during these forms of motor imagery. In terms of the focus of this thesis, however, it is important to differentiate between an effect that has statistical significance and one that has physiological significance. In these experiments, such a small effect size suggests that there is no difference between response times in the restricted and unrestricted conditions, however in the current collection of experiments it is the interaction between restriction and other factors that is of primary interest, therefore caution should be taken before excluding an interaction effect of restriction on motor imagery ability. We can conclude that the evaluative assumptions regarding the lack of significant effect of restriction on response times made in the experimental chapters are supported by the findings of this meta-analysis.

As mentioned throughout this thesis, there is research to suggest that restriction or the inability to perform movement can have a significant impact on our ability to perform motor imagery tasks (Moreau, 2012; Nico et al, 2005; Hartman et al, 2011). The lack of effect found in these studies, however, suggests that the level of disruption that restriction can have on our motor imagery performance could be influenced by other factors such as the type of restriction or disablement employed, for example permanent versus temporary, physically enforced or mentally maintained, and by the tasks involved as it is suggested that many of the tasks used in this thesis can be completed using visual as opposed to motor techniques (see discussion chapters). It is clear that more research is needed in this area in order to fully understand the effect restriction can have on our motor imagery ability, and in turn the role that our immediate bodily functions have on our cognitive ability, however the combined results of these studies suggest that the level of restriction employed in these tasks had no significant effect on participants motor imagery ability.

6.2 Experimental summary

A summary in table form can be found in Table 6.1, which outlines significant main effects and interactions involving Restriction across all of the Experiments.

It was predicted throughout this thesis that restricting motor ability in the body part associated with mental simulation task being performed would result in a disruption to mental simulation ability. This prediction was based on previous research which has demonstrated that changes to motor ability, be it through injury or experimental manipulation, can have a significant impact on our ability to perform specific motor simulations (Nico et al, 2004; Ambrosini et al, 2011).

Previous experiments have typically focused on changes to the posture of body parts to make them incompatible with the posture of the stimulus being rotated (Parsons, 1994), therefore this thesis focused on the effect of restriction when the posture remained compatible with the stimulus but the ability to move freely was manipulated. The primary aim of this research was to investigate whether changes in action ability, but not posture, can have a negative impact upon simulation ability and also whether differences exist between different types of simulations. If differences between the effects of restriction exist across the simulation types it can be concluded that the processes involved in the performance of simulations differ according to the nature of the simulations themselves, a finding which would have significant impact upon our current understanding of mental simulations.

The experiments in this thesis were separated into three different areas in order to investigate whether differences exist between the processes involved in these different simulations. These areas primarily focused on simulations that

Table 6.1. Summary of significant main effects and interactions of Restriction across Experiments 1-7

Experiment	Significant results of Restriction
1a	No significant main effect or interactions
1b	No significant main effect or interactions
2	No significant main effect or interactions
3a	No significant main effect or interactions
3b	Error: ***Restriction x Response:*** F(1,29)=5.768, p=0.021*, η_p^2 = 0.166
4a	No significant main effect or interactions
4b	Error: ***Restriction:*** F (1, 29) =5.314, p=0.029, η_p^2 =0.155 ***Restriction x Object Presentation:*** F (1, 29) =4.653, p=0.039*, η_p^2 =
4c	Error: ***Restriction x Object Presentation:*** F(1,29)=5.477, p=0.026*, η_p^2 = 0.159
5a	***Restriction x Rotation:*** F(7,161)=2.154, p=0.041*, η_p^2 =0.086
5b	No significant main effect or interactions
6a	Error: ***Restriction:*** F(1,29)=8.595, p=0.007*, η_p^2 =0.229 ***Restriction x Rotation:*** F(7,203)=3.191, p=0.003**, η_p^2 =0.099
6b	No significant main effect or interactions
7a	***Restriction x Reach Speed:*** F(2,56)=6.542, p=0.003**, η_p^2 =0.189
7b	***Restriction:*** F(1,29)=84.596, p<0.001**, η_p^2 =0.745 ***Restriction x Reach Direction:*** F(1,29)=5.373, p=0.028*, η_p^2 = 0.132 ***Restriction x Reach Speed:*** F(2,58)= 134.507, p<0.001**, η_p^2 = 0.823 ***Restriction x Reach Direction x Reach Speed:*** F(2,58)=7.625, p=0.002**, η_p^2 =0.208
7c	***Restriction x Reach Speed:*** F(2,56)=8.182, p<0.001**, η_p^2 =0.226
	*Significant to the 0.05 level ** Significant to the 0.005 level

occur unconsciously through the observation of objects; simulations that occur when performing conscious mental transformations of objects and hands; and simulations that occur consciously through the observation of actions. The results of these studies demonstrated important differences between the processes involved in the different simulations and have significant implications regarding our understanding of the role of the body in cognition.

6.2.1 Action Simulation and Affordance detection

The first series of studies investigated the effect of action restriction on affordance detection. The theory of affordances has two main components- firstly, that objects automatically communicate the actions they afford to the observer, resulting in the automatic activation of the motor codes associated with those actions (Ellis and Tucker, 2000) and secondly that the affordances communicated by an object are constrained by the sensory-motor abilities of the observer (Gibson, 1979). Affordance research demonstrates that the actions associated with an object are automatically communicated to the individual even without any intention to physically interact with the object, as demonstrated by the motor resonance effect found upon viewing an interactable object (Murata et al, 1997). This motor activation leads to the unconscious simulation of the interaction itself, leading to a potentiation of the appropriate actions required for physical interaction. Gibson (1979) believed that the actions communicated by an object at a particular time are constrained by the sensory and motor capabilities of the individual. An extension of this theory is that an inability to perform a specific action at a given moment will result in the compatible affordances of the object becoming less salient to the individual; it was this assumption that was investigated in the first series of experiments for this thesis.

Experiment 1 focused on the effects of restriction on explicit affordance based judgements of stimuli using a very simple object handedness judgement paradigm. This paradigm was used in order to determine whether restriction effects could be found when making explicit judgements of the most salient affordances of an object. The results indicated that restriction of the compatible actions had no significant effect on participants' ability to access affordance information of the stimuli when either hand or voice responses were required. When the compatible actions were restricted, participants were able to make judgements with the same level of speed and accuracy as when unrestricted, suggesting that the temporary restriction of compatible movements does not significantly affect the ability to make affordance judgements. Experiments 2 and 3 focused on the effect of restriction on the presence of affordance effects using the Temporal Order Judgement (TOJ) and the Object based Simon Effect paradigms. These particular paradigms were chosen as the unconscious processing of object affordances has been found to significantly influence responses in these studies, indicating both that the action based properties of the object are processed and action simulations are occurring unconsciously in these paradigms. The results of Experiment 2 again indicated that the restriction of hand actions did not disrupt the processing of hand related affordances, as demonstrated by the presence of an active object bias in correctly presented trials, which suggests that restricting movement does not disrupt the simulation of motor actions. The aim of the third experiment was to determine whether restriction of compatible actions disrupts the stimulus-response compatibility effect using the object based Simon effect paradigm. The results found that restriction of the compatible actions of the object did not result in the removal of the Stimulus-Response compatibility effect during restricted trials. The results of these studies suggest that the restriction of compatible movements does not interrupt the unconscious retrieval of affordance information through simulation and therefore the judgement of action based object information is not reliant upon our current physical capabilities as first predicted.

Gibson(1979) suggested that the affordances communicated by an object are constrained by the sensory-motor abilities of the observer, therefore what we perceive the purpose of an object to be at a given time is determined not only by how we feel at that moment but also by what we can physically accomplish. The results of Experiments 1-3 demonstrated that when participants were restrained and physically incapable of interacting with an object their ability to detect the affordances of that object ,be it consciously as in Experiment 1, or unconsciously as in Experiments 2 and 3, was not significantly affected. This suggests that information regarding their current physical capability was not incorporated into the simulation as predicted. This has significant implications regarding our understanding of affordances and suggests that contrary to Gibson's (1979) theory our ability to detect an object's affordances is not determined by our current physical ability; rather it is influenced by what we are structurally capable of. In essence, if we are able to perform an action then we should be able to accurately perceive action related affordances in an object, regardless of whether we are currently able to perform that action at that moment in time.

However, it is important at this point to clarify the basis behind the predictions of this series of experiments and the implications these results have both on our hypothesis and on our understanding of the processes involved in affordances. It was predicted that restricting the motor action compatible with the affordance being processed would result in a disruption to the unconscious simulation process that occurs upon observation of an interactable object, resulting in delayed responses in the restricted conditions. This disruption was predicted to occur as the result of an update to the body schema regarding current physical capabilities to take into account the current restriction of hand actions. Simulation research suggests that when performing a simulated action, the body schema provides information regarding the up to date capabilities of the individual in order to create a physically accurate simulation (Parsons 1987 a, b). The results of the current series of experiments, however, suggest that this may not be the case and that a different type of schema is used to guide these types of simulations. Research suggests that there are two types of body representations stored within the brain- the typical schema, which contains information regarding the current positioning of the body and what its current capabilities are, and the structural schema, which represents the typical structure and capabilities of a prototypical body (Corradi- Dell' Acqua, et al, 2009). It was predicted that the typical schema would provide information to the simulation regarding current physical capabilities, however the lack of restriction effect found when observing an object suggests that when required to make structural action based judgements of an object, such as handedness, we access the structural schema in order to gain information about a prototypical body's capabilities and body part positioning. This schema doesn't contain information about our own body's current capabilities; therefore the restriction will not be represented in this schema and will not affect subsequent simulations and judgements. The presence of a significant effect of restriction in Experiment 7, however, suggests that when watching someone else perform an action which we are required to make a judgement upon, the typical body schema is used to inform this simulation which contains information regarding our own body's current capabilities and positioning. As a result, when participants are restricted and are required to make these types of judgements the restriction is represented in subsequent simulations, resulting in a decline in judgement accuracy as demonstrated in Experiment 7. If different schemas are used to inform different types of simulations, as these findings would suggest, this would therefore explain the lack of significant effect of restriction as found in the current experiments and the presence of an effect of restriction found in Experiment 7.

6.2.2 Mental rotations of 3D objects and hands

The previous series of experiments focused on the unconscious simulation of motor actions therefore the second and third series of experiments focused on the effect of restriction on the conscious mental transformations of objects and hand stimuli in order to further investigate the effect of restriction on simulation ability in these experiments. The findings of these experiments, coupled with the findings of the first series, have led to the conclusion that very specific motor information is required for performance of these simulations, which has significant implications regarding our understanding of the embodied processes involved in these specific tasks.

3D Object stimuli

The aim of Experiment 4 was to determine whether restriction effects occur during the mental rotations of 3D objects. Unlike tools or body parts, abstract shapes do not have any affordances related to them and therefore observation of them alone would not result in motor activations. To account for this, the objects were framed as being 3D interactable objects which needed transforming to fit into a hole, in order to encourage belief that these were manipulatable objects that would need physical interaction to rotate. Again, it was predicted that if current physical capabilities are taken into account when performing mental simulations of compatible movements, responses in the restricted conditions would be significantly slower than responses in the unrestricted condition. The results of these studies indicated that although mental rotation was taking place, as evidenced by the presence of a significant main effect of rotation angle on response, these rotations were not mediated by the restriction of compatible actions. In Experiment 4b and c, participants were asked to actively imagine themselves to be reaching out and performing the rotations physically with their own hands in order to encourage robust motor simulations of the action but again the results indicated that although mental rotations were taking place the restriction of compatible hand movement did not disrupt the rotation process. It was suggested that the lack of significant effect of restriction could be the result of visual as opposed to motor techniques being used to perform the mental rotations in these studies as research has shown that the level of motor activation in these types of task can be dependent upon other factors. For example, research suggests that the strategies used to perform mental rotations can be manipulated through the performance of motor tasks prior to or during mental rotation tasks. Kosslyn, Thompson, Wraga and Alpert (2001) found that when participants viewed an object being rotated by a motor and were subsequently asked to perform the mental rotation task, no activation was found in the motor cortex; however when participants were asked to manually rotate the objects and then perform the mental rotation task, motor cortex activation was shown to occur. Similar results were found by Wraga, Thompson, Alpert and Kosslyn (2003), who found that when participants performed a task involving body parts prior to the mental rotation of an abstract object, motor activations occurred in the motor cortex, however when the task involves other items that did not include body parts, no such activations were found. The findings of these studies suggest that individuals can use at least two differing methods in order to perform mental rotations of abstract objects and the level of motor activation upon performance of these tasks is dependent upon the methods used. Recent findings by Moreau (2012) into this area, however, suggest that the strategies used to perform mental rotations are not necessarily dependent upon the type of stimuli but can also be influenced by the individual performing the rotations. In their study, Moreau (2012) investigated the effect of simultaneous motor tasks on the mental rotation performance of wrestlers and non-wrestlers in order to determine whether the strategies used during mental rotations are influenced by the level of expertise in sensory motor interactions. The results of their study indicated that the wrestlers, who were chosen because of the high level of motor interaction involved in their sport, were significantly disrupted when performing motor tasks alongside mental rotations of 3D abstract objects whereas non-wrestlers were not affected. They concluded that wrestlers used embodied techniques during mental rotation tasks and viewed 3D objects as manipulatable objects; therefore performance of a motor task disrupted the motor simulation that was occurring during the mental rotation. In contrast, non-wrestlers viewed the objects as non manipulatable and used basic visuospatial techniques to perform the rotation; therefore performance of a concurrent motor task did not disrupt their ability to perform the mental rotation task. The findings of these studies suggest that a number of different strategies can be employed for the completion of a mental rotation task, some of which require motor processes to complete and others that rely on purely visual processes, and that these strategies can be manipulated using various techniques. This therefore suggests that the level of motor activation involved in the mental rotation of objects is variable and is influenced by a number of different factors, some of which are beyond our control. The presence of a rotation effect in these studies is therefore not a reliable indication that motor activations, and therefore a simulation of actions, is taking place even when active imagery is occurring, and suggests that the mental rotation of a manipulatable object can be conducted on a purely visual level.

Hand stimuli

The aim of Experiments 5 and 6 was to determine whether restricting motor action significantly affected the performance of mental rotations of hand stimuli. Experiment 5 used a stimuli comparison paradigm similar to those used in typical object rotation studies and found no significant effect of restriction on rotation ability, regardless of whether the two stimuli were in presentations directly visually comparable or not. According to previous research, accurate mental rotations of body parts are performed by mentally simulating movement of one's own hand until it falls into line with the test stimulus, resulting in activations in the compatible motor area (Parsons, 1994). However, as discussed in Chapter 4, it is possible that visual techniques were used to perform this type of rotation as the task involved directly comparing two stimuli with each other; therefore Experiment 6 reverted to the laterality task typically used to investigate mental rotations of body part stimuli. Again, the results indicated no significant effect of restriction on the ability to perform mental rotations of compatible body part stimuli. These findings have significant implications regarding the bodily processes involved in the mental rotations of hands and suggest that the current ability to move those body parts is not a prerequisite for accurate mental rotations.

Previous research into the mental rotation of body parts has typically focused on the effect of manipulating the posture of the compatible body part on mental rotation ability, with results indicating a significant disturbance in rotation ability when the two are incompatible (Parsons, 1994). In the current studies, hand posture remained consistent throughout and the results indicated no significant difference in rotation performance when restrained or unrestrained. This could therefore suggest that the most critical information required for the performance of mental rotations of body parts is the current position of the body part, as it is this position that the rotation will begin from, and not the current physical capability of the hand. If this is indeed the case then this would suggest that in conditions where the hand posture is compatible with that of the stimuli, as occurred in these studies, there will be no disturbance in the rotation ability. This, combined with the possible use of the structural schema as opposed to the typical schema to inform the simulations, could provide an explanation for the lack of significant effect of restriction on mental rotation ability. As previously explained, the structural schema contains information regarding typical structural abilities of body parts; therefore if the structural schema is used to perform these transformations then we would not expect to find any significant effect of restriction on rotation performance. Research into amputee patients' ability to perform mental rotations of their missing body part has demonstrated the presence of intact mental rotation ability of corresponding body parts in amputee patients, albeit with higher levels of inaccuracy, which would suggest that the structural schema is involved in these transformations (Nico et al, 2004). These individuals had previously experienced physical hand movements therefore the mental representation of the relevant body part contained accurate information regarding the physical capabilities of that limb on which to base their simulations. Nico et al (2004) suggested that the high levels of inaccuracy found in these studies was not the result of an inability to physically perform the rotation but rather the result of a lack of information regarding the current postural positioning of the body part upon which to start the transformations, making mental simulation of the body part very difficult. This suggests that in order to perform a mental rotation of a body part, the current positioning of the coordinating limb is required as this is the starting position for the transformation, however information regarding the general physical capabilities of the limb is then used to guide the subsequent simulation.

The findings of these studies suggest that temporary, or even permanent, changes to physical ability are not represented in mental rotations of body parts and the current ability to perform the corresponding motor action is not required for accurate mental rotation performance. This finding therefore leads to the conclusion that these simulations are performed based on information contained in the mental representation regarding the movements typically within ones repertoire and not on current physical capabilities and are largely driven by the current positioning of the body part, not its immediate ability to move.

6.2.3 Time to Contact judgements

The final series of experiments in this series focused on the effect of action restriction on our ability to simulate the actions of others. The previous experiments in this thesis have focused on simulations that occur when making judgements on stationary stimuli and found no significant effect of restriction on any of these paradigms. It was therefore decided that the final series of experiments would focus on simulations that occur as the result of observing an action performed by another individual. This area of research has gained popularity in recent years in an attempt to broaden our understanding of the mediatory factors influencing mirror neurons. Research has discovered that observation of another individual performing an action (with a perceived goal) that is within one's repertoire results in activation of so called "mirror neurons", which leads to the activation of the appropriate motor areas involved in performance of this action. Mirror neuron research has found, however, that mirror neurons not only reflect the actions observed onto the observer's neural network but also the situational parameters of those actions. For example, Liepelt et al (2009) found that observing another individual being constrained significantly influenced the subsequent performance of compatible actions, even though the participants observing suffered from no form of physical restraint. This suggests that mirror neurons are sensitive to situational performance factors and reflect them in their own activations and subsequent performance. In light of this research, the aim of the final series of experiments was to determine whether the restriction of a reaching movement in the observer would significantly impact on their ability to perceive the performance factors of another individuals action, in this case the effect of the speed of reach on time to contact judgements, by disrupting the mental simulation process.

The results of Experiments 7a, b and c universally demonstrated a significant effect of restriction on the ability to accurately represent the speed of the observed action, with the presence of a significant interaction between restriction and reaching speed across all experiments. This suggests that the current availability of actions of the observer is taken into consideration when performing simulations of other people's actions, resulting in a simulation that reflects their current physical capabilities. If extended, this could suggest that the ability to currently perform an action significantly impacts on our ability to understand the parameters of that action when performed by another individual, suggesting a shift for action understanding to interaction understanding. Similar research in this area supports this theory and has shown a significant effect of restriction on the ability to judge the target object of a reaching action, which suggests that restricting movements can have a significant effect on our ability to predict the intentions of other people's actions(Ambrosini et al, 2011). This finding has significant impact on our understanding of the processes involved in the observation of actions and also on our understanding of the factors that affect mirror neurons. Previous research has demonstrated that when we observe another individual performing a goal related action within our repertoire the neural systems that would fire when performing that action physically are automatically activated (Gallese et al, 1996). In the current studies, mirror neurons would be activated upon observation of the reaching action, resulting in a simulation of the reaching movement being observed including any performance information such as speed of movement. The presence of a restriction effect in these studies, coupled with the lack of a significant restriction effect in the other studies in this thesis, lead to the conclusion that the presence of a restriction effect depends upon the nature of the event being judged, i.e. object or action, and more importantly, the class of neurons that are activated as a result of it. In the current series of experiments, participants observed another individual reaching towards an object with the intention of interacting with it and were required to make a judgement of when they predicted contact with the object would be made. In order to accurately predict the point of contact in these studies, participants need to mentally simulate the reaching action of the other individual including action information such as the speed of movement. The presence of a significant interaction between restriction and speed across all experiments suggests that restriction disrupted the simulation of the reaching action and more importantly prevented the processing of the action based information included in the observed reach to enable accurate representation of the speed of reach into the simulation. The results of these studies suggest that the current unavailability of a compatible action was incorporated into the mental simulation, which suggests that simulations that result from activation of the mirror neurons are influenced by bodily information contained in the typical schema, and are therefore significantly affected by the restriction of compatible movements. This finding, coupled with the restriction effect demonstrated in Ambrosini et al's (2011) study, can be extended to suggest that in order to accurately understand someone else's actions, one must be able to perform the corresponding action themselves at that moment in time, whereas one does not need to in order to understand the action based features of an object. If this assumption is accurate, and the results of the current body of research suggests it may be, then this would suggest a direct link between our physical capabilities and our understanding of actions, thereby providing strong support for the Embodied theory of Cognition. This, combined with the lack of significant effect of restriction in the other studies in this thesis, therefore suggests that restriction has a significant disruptive effect on the action simulation of an observed motor action but not on simulations relating to imagined interactions or transformations of static objects or limbs which has serious implication regarding our understanding of the body's role in our Cognitive development.

It can also be argued that individuals may have very little experience of mental rotation but most will be well versed in the observation of actions as performed by others. This could therefore suggest that the effect of restriction found in Experiment 7 could be due to the familiarity of the action being observed and the practice that the individuals have in performing the action themselves. If this is indeed the case, then this could suggests that the familiarity of the task, and indeed the amount of practice that we ourselves have had performing the task in our everyday lives, might be a contributing factor towards the effect of restriction on our performance. This would therefore suggest that it is only once we have become well trained in an action or task that our motor systems become involved in the interactions.

It is worth noting at this point that the restriction methods used in this task differed from those used in the other experiments in this thesis, which may have been a contributing factor to the significant effect of restriction found in these experiments. In Experiments 1-6, participants had their hands restricted firmly in front of themselves to prevent arm movement of any kind. Their hand and arms were strapped down and therefore were physically restricted. In Experiment 7, however, participants held their hands and arms behind their backs and were required to physically maintain the restriction themselves. As a result of this, participants could have been under more mental strain in Experiment 7 during the restricted trials due to having to actively maintain their limb restraint which could have influenced their performance in the study. There is a wide scope of research investigating the effect of mental load on cognitive performance which suggests that the performance of concurrent tasks can influence visual perception (Recarte, Pérez, Conchillo, & Nunes, 2008), which could suggest that the effect of restriction found in Experiment 7 may actually be in part due to the increased attention attributed to the maintaining of the restricted movements. In order to investigate whether this is indeed the case, further studies should be conducted with a range of restriction methods involving different levels of attentional and cognitive load to determine whether this is a contributing factor.

6.3 Implications for Embodied Cognition

The aim of this research was to investigate whether the immediate ability to perform an action has a significant effect on the performance of mental simulations of compatible actions. It was predicted that restricting motor performance in tasks where the motor simulation of that action occurs would have a significant impact on individuals' ability to perform accurate mental simulations as the current inability to act would be incorporated into the simulation by the body schema. The overarching aim of this thesis, however, was to investigate the extent of the role the body plays in our ability to perform such cognitive actions. The results of these studies individually suggest very little however it is the combination of the results together that provide us with a greater insight into the role our bodies play in these interactions.

The results of Experiments 1-6 all indicate, on the surface, that restricting movements involved in physical interaction with the stimuli had no significant effect on one's ability to perform mental simulations of those interactions. The lack of significant findings in these studies could suggest that the body is not involved in these types of simulations and that visual techniques are being used instead. Indeed, research by Ganis et al (2000) into the motor activations that occur upon mental rotation of body parts found that mental representations of the body part, which will include the relevant structural limitation information regarding that particular limb, are only accessed at least 400ms after the beginning of the trial. Before this point visual-spatial techniques are used to perform the rotation which suggests that the mental rotation of body parts can be performed without activation of the motor cortex. However, when the results of Experiments 1-7 are taken into account collectively this suggest that different motor mechanisms may be used during the different simulations, leading to the conclusion that the body plays a different role in each of these tasks. A key assumption of this thesis was that the simulations that occurred during all of these tasks would be mediated by the body schema which should take into account changes to the body's capability; therefore restriction of the compatible movements should be incorporated into the simulations by the schema resulting in a disruption to the simulation as compatible with real life movement ability. This prediction was supported by previous restriction and simulation research (Ambrosini et al, 2011, Craighero & Zorzi, 2012), however the results of this collection of studies suggests that the lack of significant effect of restriction in Experiments 1-6 may be the result of a different body schema being used to inform the mental simulations than in Experiment 7. This in turn suggests that our body plays a different role in these cognitive tasks, despite the fact that the same mental process, i.e. a mental simulation of action, is being performed. It is critical at this point to point out that although on the surface the same processes were involved in the completion of these tasks, the key difference between them lies in the neurons that are activated upon observation of the stimuli. Research has found that there are two distinct types of visuo-motor neurons in the brain- canonical neurons, which respond upon observation of an object, and mirror neurons, which respond when an action performed by another individual is observed (Gallese et al, 1996). In Experiment 7, participants observed another individual reaching towards an object, whereas in the other experiments participants made judgements of static stimuli without the observation of any overt motor actions being performed. It is therefore possible that the restriction effect found in Experiment 7 and the subsequent lack of significant effect of restriction in any of the other experiments was a direct result of the observation of an action being performed, which leads to the conclusion that the effect of restriction on simulation ability could be influenced by the type of visuomotor neurons activated during the simulation task. In Experiment 7 mirror neurons would be activated whereas Experiments 1-6 would only result in the activation of canonical neurons as no actions are observed, which indicates that the canonical neurons are resistant to changes in current performance ability whereas mirror neurons are not. This suggests that canonical and mirror neurons rely on different types of body schema upon which to base their simulations. If this is indeed the case, then we should expect other tasks which involve the mirror system, i.e. tasks that involve either the observation or the performance of an action (Aziz-Zadeh & Ivry, 2009) to be equally affected by changes to the current physical capabilities of the observing individual. Further research is needed in this area before a firm conclusion can be made therefore future experiments should be focused on investigating the effect of restriction on tasks involving the observation of other peoples' actions in order to determine whether this is indeed the case.

The findings of the experiments conducted in this thesis have some very important consequences for the Embodied Cognition theory. Indeed perhaps the most interesting finding to arise from this series of studies is the notion that our ability to understand another person's actions, or at least the physical parameters of those actions, is directly related to our current physical capabilities. This therefore suggests a direct link between our body and our cognitions, an idea posited by Barsalou's (2003) theory of Embodied Cognition. However, another important finding from this series of research is that not all motor tasks automatically need motor input to be able to be completed accurately and in a timely fashion. The lack of significant effect of Restriction found in the mental rotation tasks in Experiments 4, 5 and 6 is possibly due to the use of the structural schema to perform the simulations however it is also possible that visual techniques were used to perform those tasks without motor activations being involved. In Experiments 4 and 5 particularly, it is possible that the task was accurately performed by using visuospatial techniques to mentally rotate the stimuli rather than imagining transformation of the participant's own hand. This is a finding supported by neuroimaging research, which has shown that mental representations, and subsequent motor activations, are only accessed and used part way through mental rotation tasks. Before this point, visual techniques are used instead (Ganis et al, 2000). It is therefore possible that motor activations are only involved in the completion of these types of tasks when visual techniques fail suggesting that in these cases it may not have been necessary to involve the motor system to perform the rotations. In Experiment 7, however, participants would need to perform a motor simulation of the reaching movement in order to make an accurate judgement therefore activation of the motor system was required. If these assumptions are accurate then this would suggest that motor techniques are implemented as a second rather than first choice in these types of situations, a suggestion which has serious implications for the Embodied Cognition Theory as it would suggest that the mind and body can operate on a relatively independent level. However, even if this is the case, it does not necessarily suggest that the body and mind do not also operate cooperatively at times, as demonstrated in Experiment 7. There is sufficient evidence from both these studies and others in the field to suggest that motor activations do occur during mental simulations and that these activations can improve and inhibit subsequent actions, and vice versa, however the results of these studies suggest that these activations may exist in the background and are implemented when needed (Richter et al, 2000, Wexler et al, 1998). This leads to the suggestion of a more sedate relationship between the two entities, with cooperation between them when needed. Further research is obviously needed into this area before any firm conclusions can be made regarding the motor system's influence and role in these situations.

The experiments in this thesis used a combination of 3 different response methods- hand response, foot response and voice response- consistent with other experiments conducted in this area (Ganis et al, 2000; Ambrosini et al, 2011; Craighero & Zorzi, 2012; Moreau, 2013). However, the results of Experiments 1-6 indicated no difference in the effect of restriction on responses across the three effectors. Previous research into simulations has used a combination of these different response types and there is justification for the use of all in this area of research. For example, in experiments where a hand response is potentiated by an object or action, hand responses should be most affected by the restriction effect as responses in unrestricted conditions would be facilitated by the activation of the appropriate action codes whereas the unavailability of the action in the restricted conditions should result in a disruption to the simulation, resulting in significantly slower responses when using a hand response in these conditions (Craighero & Zorzi, 2012). However, it can also be argued that hand responses in the restricted condition, however minimal, may undermine the restriction by signalling to the body schema that movement in the hand is available (Wexler et al, 1998). If this is indeed true, then it would be difficult to attribute any differences in responses between the two restriction conditions to the restriction of actions as actions are still available to be performed. Foot responses have been used in these types of experiment in order to account for these effects however research has also indicated that these types of responses may compromise the restriction effect through the transferring of motor activations. Schicke and Roder (2006) suggested that motor functions such as reaching and grasping are coded separately within the brain but as these tasks can be accomplished using various different effectors, such as both hands and feet, they are not coded according to a specific limb but rather the appropriate effector is chosen according to the situation. As a consequence of this, foot responses can also be facilitated through perception of an object or action. In the studies in this thesis the objects could not be physically interacted with therefore it is plausible that restriction of the hand action resulted in the potentiation of a foot response instead, thereby counteracting any possible restriction effect.

The final response method used for these studies, and the one most typically used in simulation research, is that of voice responses. This method is typically used in order to avoid any potential disruptive effects resulting in the performance of a motor action alongside mental simulations (Wexler et al, 1998). However, no significant restriction effects was found in Experiments 1-6 using any of these methods, which suggests that when hands were restricted simulations of actions were performed at the same speed as when the appropriate action was available, regardless of the response method. This lack of restriction effect suggests not only that objects do not potentiate specific motor actions to be completed by one effector alone, an idea supported by the TEC (Hommel, et al 2001), but also highlights the flexibility of the body schema in these situations. This finding has serious implication regarding our understanding of the representation of actions and objects in the body schema and it is clear that further research is needed in this area before we fully understand the relationship between the two. However, these findings also demonstrate the robustness of the body schema and its adaptability in situations such as these.

The results of these studies have collectively shown that the motor system can play a variable robe in our cognitions. The lack of significant effect of restriction in the majority of these studies, coupled with the suggestions of visual techniques being involved in completion of the tasks, would suggest a much less dependent role of the body in cognitive performance than is posited by Barsalou's (2003) Embodied Cognition theory and brings into question the exact role of our body in these tasks. It is obvious that further research needs to be conducted into this area before any firm conclusions can be made but the findings of these studies would suggest that our bodies are not inextricable from our cognitions and that at both can work relatively independently from each other when required. This therefore brings into doubt Barsalou's (2003) theory of Embodied Cognition and suggests a much more flexible and independent relationship between body and cognition.

Future research

The results of this thesis have led to the conclusion that different body schemas are involved in the mental simulations of actions, with information regarding current physical capabilities used for simulations of the actions of others and information regarding the typical structure of a body in general used for other types of action based simulations, such as the affordances of objects and simulations of hand rotations. There are still many unanswered questions, however, regarding why different schemas are used for different simulations and whether this varies according to certain factors, for example egotistical presentation of stimuli, active interaction with the stimuli etc. Further research therefore needs to be conducted into this area in order to determine whether the use of different schemas is the result of specific visuomotor neuron activation as previously suggested or whether there are other factors influencing their implementation. For example, the tasks used in Experiment 1-6 involved participants making general judgements relating to visual stimuli. As a consequence of this, simulations may have used the structural schema to provide information as the stimuli were not directly related to the participants; therefore information regarding their current capabilities was not needed. These experiments could therefore be repeated with manipulations included to encourage egocentric perception of the stimuli to investigate whether this can influence the body schema used for these simulations. It is also worth noting that real objects were not used during these experiments therefore future studies could include images of real and interactable objects in order to produce more ecologically valid scenes in order to determine whether this has an impact on the effect of restriction in these tasks. This would also help us to understand more fully the role that our current bodily capabilities play on our cognitive processes.

The results of Experiment 7 suggest that current physical capabilities have a significant effect on our ability to simulate and understand the actions of others. This finding is supported by research by Ambrosini et al (2011) who found a significant effect of restriction on participants' ability to judge the intended target of a reaching action. This finding leads to the assumption that information about our body's capabilities is included in the mental simulations of other peoples actions, which suggests that simulations resulting from mirror neuron activations are developed using information about current physical capabilities, suggesting a direct link between our body and our cognitive ability. This finding has significant implications regarding the processes involved in the understanding of actions as it suggests that in order to accurately understand the intentions and dynamics of the actions of other we need to be able to perform those actions ourselves at the current time. It is clear, however that before a definite conclusion can be made regarding this assumption further research needs to be conducted into other tasks that involve mirror neuron and canonical neuron activations. If a significant effect of restriction is found in mirror neuron tasks alone then it could be concluded that simulations resulting from mirror neurons activation are performed using current bodily information whereas those that don't are performed using other techniques.

Previous research has shown that the mechanisms used to perform task such as mental rotations can vary with regards to the level of motor involvement and can manipulated by various means, which suggests that the involvement of motor areas is fairly fluid and can be determined by other influencing factors (Kosslyn et al, 2001). This research suggests that the motor system is not always immediately involved in motor tasks and its implementation can be triggered by varying factors, such as the simultaneous performance of other motor actions. For example, Ganis et al (2002) demonstrated that access to the mental representation of body parts does not occur until at least 400ms into a mental rotation task, before which visual techniques are used. It is unclear after this point, however, exactly what level of input the motor system has in the rotations, i.e. whether the motor system automatically takes over performance of the rotations or works alongside the visual system. It is therefore important to establish exactly what role the motor system plays in these types of tasks and whether one system, i.e. visual or motor, is more dominant than the other. As a consequence of this, further research is needed in order to fully understand the processes involved in these different tasks and what factors, if any, can affect these processes.

The restriction methods used in this series of experiments were designed to prevent the performance of action associated with the movement or action being mentally simulated, for example grasping movements in the affordance based tasks, hand rotations in the rotation task and a reaching movement in the time to contact studies. The presence of a restriction effect in Experiment 7 suggests that the restriction method employed significantly influenced the judgement of the action parameters of a reaching behaviour in another individual. The method used prevented a reaching action from being performed, however further research needs to be conducted in this area in order to determine whether the restriction of very specific movements, for example hand shaping, can result in a similar disruption to simulations and influence participants judgements of actions compatible with those movements. For example, when reaching towards an object, the hand will start shaping from the beginning of the reach until contact is made with the object, starting off with a wider hand aperture and re-scaling itself as it comes closer to the object (Jeannerod, 1984). This movement provides important cues regarding the distance from an object, as well as an indication of the time to contact. A possible future study could involve the restriction of a grasping action during observation of a reaching movement towards an object in order to determine whether restriction of a prehension movement interrupts the simulation of that action, resulting in impaired judgement of the time of contact of the movement using the information provided in the hand grasp. If this occurs, this would provide further support for the theory that our ability to perform an action is directly related to our ability to understand the actions of others.

6.4 Conclusion

The research reported in this thesis provides some compelling findings in support of the Embodied Cognition theory but also highlights the general vulnerability of the theory in general. The presence of a significant effect of restriction on the ability to understand other people's actions suggests a direct relationship between the body and cognition, an idea which forms the cornerstone of Embodied Cognition research; however the potential for purely visual techniques to be implemented in the other experiments in this series, coupled with research demonstrating the changeable involvement of the motor system dependent on the presence of other factors (Wraga et al, 2003), suggest that the body's involvement in our cognitions is not as straight forward as previously thought. It is clear from this research that the body does play an important role in the development of our cognitions, and vice versa, however the findings of these studies do suggest that our cognitions are not generally influenced on a moment by moment basis by our current physical abilities as previously predicted. Indeed, to even suggest this would, in some respect, seem ridiculous, however the presence of a significant effect of restriction on our ability to judge the actions of other, as demonstrated in Experiment 7, does suggest that on some level this statement is true. As a consequence of this, it appears that the contribution our body plays in shaping our cognitions varies depending on what we are trying to accomplish and the resources available to us at a given time. Connell & Lynott (2014) suggest that it is impossible to represent the same concept twice as changes in situational aspects, motivation and goals can all influence the simulation that takes place, therefore we would expect that the level of involvement of the motor system in simulations to change in relation to these various aspects. Whether this contribution is automatically moderated or within our control is still under debate, and it could even be suggested that the motor system only gets involved when the visual system fails, however the results of these studies do suggest a level of involvement of the body in our everyday cognitions providing support for the Embodied Cognition theory. However, the variability of its role demonstrates that further investigation into the extent of the factors surrounding its involvement is needed before firm conclusions can be made regarding its contribution to our Cognitive development.

Chapter 7: Appendix 1

7.1 Statistical analysis for Experiment 1a

7.1.1. Table of means, standard error and mean errors for Experiment 1a by conditions.

	Response/Handle location	
Restriction	Left	Right
Restricted	**584.92** 102.32 (0.73)	**582.3** 115.83 (0.60)
Unrestricted	**576.38** 98.77 (0.36)	**567.9** 87.53 (0.33)

7.1.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value
Restriction	1	3944.162	3944.162	1.104	0.302
Response/handle	1	924.648	924.648	0.514	0.479
Rest*Resp/handle	1	257.477	257.477	0.419	0.523

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value
Restriction	1	3.008	3.008	0.645	0.428
Response/handle	1	0.208	0.208	0.355	0.556
Rest*Resp/handle	1	0.075	0.075	0.113	0.739

7.2. Statistical analysis for Experiment 1b

7.2.1. Table of means, standard error and mean errors for Experiment 1b by conditions.

	Response	
Restriction	Left	Right
Restricted	**742.14** 111.28 (0.10)	**730.58** 111.84 (0.067)
Unrestricted	**738.25** 109.2 (0.167)	**728.19** 113.56 (.200)

7.2.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value
Restriction	1	295.693	295.693	0.113	0.739
Response/handle	1	3506.116	3506.116	1.74	0.197
Rest*Resp/handle	1	16.95	16.95	0.039	0.844

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value
Restriction	1	0.3	0.3	2.351	0.136
Response/handle	1	*	*	*	1
Rest*Resp/handle	1	0.033	0.033	0.326	0.573

7.3. Statistical analysis for Experiment 2

7.3.1. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means- Active objects first

Source	DF	SS	MS	F	P value	Power
Restriction	1	3.285	3.285	0.213	0.648	0.073
Pairing	1	23.16	23.16	2.26	0.143	0.307
Presentation	1	65.004	65.004	7.436	0.011	0.751
Response order	1	0.004	0.004	*	0.996	0.05
Rest*Resp order	1	7.223	7.223	0.468	0.499	0.102
Pair*Resp order	1	0.004	0.004	*	0.985	0.05
Pres*Resp order	1	49.879	49.879	5.706	0.023	0.638
Rest*Pair	1	3.754	3.754	0.499	0.485	0.105
Rest*Pres	1	2.848	2.848	0.614	0.439	0.118
Pair*Pres	1	0.098	0.098	0.014	0.908	0.051
Rest*Pair*Resp order	1	1.41	1.41	0.188	0.668	0.07
Rest*Pres*Resp order	1	7.223	7.223	1.558	0.222	0.227
Pair*Pres*Resp order	1	0.316	0.316	0.044	0.835	0.055
Rest*Pair*Pres	1	0.316	0.316	0.102	0.751	0.061
Rest*Pair*Pres*Resp	1	10.16	10.16	3.29	0.08	0.419

ii) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means- Passive objects first

Source	DF	SS	MS	F	P value	Power
Restriction	1	29.566	29.566	1.397	0.246	0.208
Pairing	1	4.785	4.785	0.992	0.327	0.161
Presentation	1	226.879	226.879	18.86	0.0001*	0.987
Response order	1	692.348	692.348	2.905	0.099	0.378
Rest*Resp order	1	36.754	36.754	1.737	0.198	0.248
Pair*Resp order	1	25.629	25.629	5.314	0.028	0.607
Pres*Resp order	1	32.348	32.348	2.689	0.111	0.355
Rest*Pair	1	12.691	12.691	1.559	0.221	0.227
Rest*Pres	1	7.223	7.223	1.868	0.182	0.263
Pair*Pres	1	2.066	2.066	0.357	0.555	0.089
Rest*Pair*Resp order	1	4.254	4.254	0.523	0.475	0.108
Rest*Pres*Resp order	1	7.91	7.91	2.046	0.163	0.283
Pair*Pres*Resp order	1	0.473	0.473	0.082	0.777	0.59
Rest*Pair*Pres	1	3.754	3.754	0.736	0.398	0.132
Rest*Pair*Pres*Resp	1	2.441	2.441	0.479	0.494	0.103

iii) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means- All trials

Source	DF	SS	MS	F	P value	Power
Restriction	1	26.281	26.281	1.614	0.214	0.233
Pairing	1	24.5	24.5	2.692	0.111	0.355
Presentation	1	267.383	267.383	16.33	0	0.974
First object	1	19527.82	19527.82	56.269	0	1
Response order	1	347.82	347.82	4.446	0.43	0.532
Rest * Resp	1	5.695	5.695	0.35	0.559	0.088
First * Resp	1	344.531	344.531	0.993	0.327	0.162
Pair * Resp	1	13.133	13.133	1.443	0.239	0.214
Pres * Resp	1	81.281	81.281	4.964	0.034	0.578
Rest * First	1	6.57	6.57	0.323	0.574	0.085
Rest * Pair	1	15.125	15.125	2.022	0.165	0.28
First * Pair	1	3.445	3.445	0.577	0.453	0.114
Rest* Pres	1	9.57	9.57	2.554	0.121	0.34
First* Pres	1	24.5	24.5	5.571	0.025	0.627
Pair * Pres	1	0.633	0.633	0.078	0.782	0.058
Rest * First* Resp	1	38.281	38.281	1.884	0.18	0.264
Rest * Pair * Resp	1	0.383	0.383	0.051	0.823	0.056
First * Pair* Resp	1	12.5	12.5	2.093	0.158	0.288
Rest * First * Pair	1	1.32	1.32	0.161	0.691	0.068
Rest * Pres* Resp	1	15.125	15.125	4.036	0.054	0.494
First * Pres* Resp	1	0.945	0.945	0.215	0.646	0.073
Rest * First * Pres	1	0.5	0.5	0.105	0.748	0.061
Pair * Pres* Resp	1	0.781	0.781	0.096	0.758	0.06
First* Pair * Pres	1	1.531	1.531	0.314	0.579	0.084
Rest* Pair * Pres	1	0.945	0.945	0.167	0.685	0.068
Rest * First* Pres* Resp	1	0.008	0.008	0.002	0.968	0.05
Rest * First* Pair* Resp	1	5.281	5.281	0.646	0.428	0.122
Rest* Pair* Pres* Resp	1	11.281	11.281	1.998	0.168	0.278

First* Pair* Pres* Resp	1	0.008	0.008	0.002	0.968	0.05
Rest* First* Pair* Pres	1	3.125	3.125	1.231	0.276	0.189
Rest* First* Pair* Pres* Resp	1	1.32	1.32	0.52	0.476	0.107

7.4. Statistical analysis for Experiment 3

7.4.1. Table of means, standard error and mean errors for Experiment 3a by conditions.

	Required Response			
	Left		Right	
	Location			
Restriction	Left	Right	Left	Right
	112.201	**121.936**	**124.449**	**114.631**
Restricted	9.362	9.2	10.442	8.872
	0.6	0.933	1	0.733
	112.204	**121.841**	**135.238**	**112.404**
Unrestricted	9.621	9.358	10.851	7.437
	7.67	0.667	1	0.4

7.4.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P Value	Power
Restriction	1	2198.801	2198.801	1.881	.181	.264
Response	1	1858.504	1858.504	1.500	.231	.220
Location	1	46.475	46.475	.117	.735	.063
Restriction * Response	1	291.121	291.121	1.358	.253	.203
Restriction * Location	1	36.979	36.979	.230	.635	.075
Response * Location	1	15511.148	15511.148	27.004	.000	.999
Restriction * Response * Location	1	612.708	612.708	2.016	.166	.279

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P Value	Power
Restriction	1	.704	.704	1.012	.323	.164
Response	1	.104	.104	.139	.712	.065
Location	1	1.504	1.504	2.374	.134	.319
Restriction * Response	1	.204	.204	.355	.556	.089
Restriction * Location	1	2.204	2.204	3.092	.089	.398
Response * Location	1	4.538	4.538	2.840	.103	.371
Restriction * Response * Location	1	.038	.038	.031	.861	.053

7.5. Statistical analysis for Experiment 3b

7.5.1. Table of means, standard error and mean errors for Experiment 3b by conditions.

	Required Response			
	Left		Right	
	Location			
Restriction	Left	Right	Left	Right
	431.051	**451.99**	**446.962**	**429.353**
Restricted	8.459	10.584	9.813	9.627
	1.233	1.667	2.633	1.4
	431.181	**444.159**	**436.295**	**423.508**
Unrestricted	9.148	10.373	9.436	7.906
	1.833	2.4	2.167	1.333

7.5.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P Value	Power
Restriction	1	2198.801	2198.801	1.881	.181	.264
Response	1	1858.504	1858.504	1.500	.231	.220
Location	1	46.475	46.475	.117	.735	.063
Restriction * Response	1	291.121	291.121	1.358	.253	.203
Restriction * Location	1	36.979	36.979	.230	.635	.075
Response * Location	1	15511.148	15511.148	27.004	.000	.999
Restriction *Response * Location	1	612.708	612.708	2.016	.166	.279

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P Value	Power
Restriction	1	2.400	2.400	3.379	.076	.428
Response	1	.600	.600	.118	.734	.063
Location	1	4.267	4.267	1.216	.279	.187
Restriction * Response	1	13.067	13.067	5.927	.021	.653
Restriction * Location	1	1.067	1.067	.704	.408	.128
Response * Location	1	35.267	35.267	9.072	.005	.829
Restriction * Response * Location	1	.267	.267	.252	.620	.077

Chapter 8: Appendix 2

8.1 Statistical analysis for Experiment 4a

8.1.1. Table of means, standard error and mean errors for Experiment 4a by conditions.

	Restriction			
	Restricted		Unrestricted	
	Presentation			
Rotation	Mirrored	Unmirrored	Mirrored	Unmirrored
0/360°	**1521.222**	**914.808**	**1587.492**	**984.678**
	77.597	40.19	95.172	44.365
	0.6	0.233	0.733	0.467
45°	**1508.138**	**1028.263**	**1512.058**	**1027.896**
	86.57	45.937	90.316	50.289
	0.367	0.433	0.367	0.167
90°	**1530.63**	**1235.329**	**1531.623**	**1300.101**
	92.044	68.116	81.428	67.107
	0.433	0.767	0.7	0.833
135°	**1455.962**	**1337.227**	**1506.529**	**1309.349**
	87.403	86.521	76.569	79.329
	0.3	2.1	0.567	2.033
180°	**1461.03**	**1270.233**	**1492.859**	**1326.405**
	78.413	75.917	82.157	60.129
	0.4	1.7	0.467	1.9
225°	**1502.894**	**1283.596**	**1479.086**	**1329.49**
	70.688	58.113	70.494	76.602
	0.5	1.1	0.633	1.433
270°	**1453.051**	**1195.202**	**1539.312**	**1179.57**
	67.367	53.553	72.854	51.774
	0.467	0.6	0.5	0.4
315°	**1460.461**	**1066.327**	**1501.854**	**1028.843**
	79.496	51.201	79.006	40.891
	0.3	0.367	0.867	0.433

8.1.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P Value	Power
Restriction	1	154405.537	154405.537	0.270	0.607	0.079
Presentation	1	24759049.432	24759049.432	97.577	0.000	1.000
Rotation	7	3667248.573	523892.653	8.699	0.000	1.000
Restriction * Presentation	1	9442.693	9442.693	0.145	0.706	0.066
Restriction * Rotation	7	111103.876	15871.982	0.477	0.851	0.206
Presentation * Rotation	7	5444572.435	777796.062	18.304	0.000	1.000
Restriction * Presentation * Rotation	7	224787.950	32112.564	1.098	0.366	0.467

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P Value	Power
Restriction	1	3.151	3.151	1.167	0.289	0.181
Presentation	1	42.926	42.926	17.616	0.000	0.982
Rotation	7	93.207	13.315	16.387	0.000	1.000
Restriction * Presentation	1	1.134	1.134	1.042	0.316	0.167
Restriction * Rotation	7	4.907	0.701	1.411	0.203	0.590
Presentation * Rotation	7	113.632	16.233	18.936	0.000	1.000
Restriction * Presentation * Rotation	7	3.324	0.475	0.815	0.575	0.347

8.2 Statistical analysis for Experiment 4b

8.2.1. Table of means, standard error and mean errors for Experiment 4b by conditions.

	Restriction			
	Restricted		Unrestricted	
	Presentation			
Rotation	Mirrored	Unmirrored	Mirrored	Unmirrored
0/360°	**1539.004**	**904.025**	**1593**	**934.696**
	61.836	28.286	81.86	31.016
	0.733	0.4	0.733	0.5
45°	**1410.74**	**988.401**	**1519.881**	**1021.009**
	62.16	35.657	70.59	37.326
	0.533	0.233	0.6	0.433
90°	**1484.87**	**1165.214**	**1473.591**	**1171.473**
	74.808	44.044	68.92	49.85
	0.5	0.4	0.633	0.667
135°	**1455.299**	**1318.798**	**1433.185**	**1339.017**
	62.016	45.984	63.017	52.183
	0.8	1.133	0.8	1.8
180°	**1481.627**	**1349.143**	**1395.862**	**1311.195**
	66.768	56.398	55.227	63.237
	0.667	1.167	0.7	1.767
225°	**1512.393**	**1286.744**	**1505.142**	**1305.058**
	69.832	47.392	67.764	60.635
	0.633	1.133	0.6	1.267
270°	**1422.576**	**1223.513**	**1481.996**	**1174.117**
	56.145	49.88	61.43	53.415
	0.567	0.8	0.567	0.967
315°	**1489.57**	**1073.117**	**1484.825**	**1081.669**
	64.064	48.24	82.013	54.627
	0.8	0.5	0.767	0.567

8.2.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value	Power
Restriction	1	12933.527	12933.527	.034	.855	.054
Presentation	1	22202370.123	22202370.123	118.316	.000	1.000
Rotation	7	3352634.133	478947.733	13.111	.000	1.000
Restriction * Presentation	1	3474.961	3474.961	.074	.787	.058
Restriction * Rotation	7	287964.391	41137.770	1.305	.250	.549
Presentation * Rotation	7	6641171.269	948738.753	26.795	.000	1.000
Restriction * Presentation * Rotation	7	161034.352	23004.907	.778	.607	.330

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value	Power
Restriction	1	5.251	5.251	5.314	.029	.606
Presentation	1	9.009	9.009	3.119	.088	.400
Rotation	7	52.882	7.555	12.079	.000	1.000
Restriction * Presentation	1	3.876	3.876	4.653	.039	.550
Restriction * Rotation	7	3.191	.456	.856	.543	.364
Presentation * Rotation	7	41.899	5.986	6.729	.000	1.000
Restriction * Presentation * Rotation	7	2.699	.386	.828	.565	.353

8.3 Statistical analysis for Experiment 4c

8.3.1. Table of means, standard error and mean errors for Experiment 4c by conditions.

	Restriction			
	Restricted		Unrestricted	
	Presentation			
Rotation	Mirrored	Unmirrored	Mirrored	Unmirrored
0/360°	**1617.937**	**1139.623**	**1647.463**	**1106.822**
	113.082	78.079	126.202	67.719
	0.967	1.2	0.567	1.233
45°	**1578.199**	**1209.837**	**1521.912**	**1221.077**
	89.414	105.359	104.171	90.933
	0.667	1.433	0.833	1.267
90°	**1662.53**	**1308.352**	**1560.287**	**1271.875**
	107.735	87.761	117.79	76.034
	0.7	1.5	0.433	1.8
135°	**1601.551**	**1454.962**	**1596.448**	**1377.297**
	123.695	102.586	114.11	85.737
	0.8	1.767	0.533	2.067
180°	**1572.344**	**1435.497**	**1567.353**	**1298.104**
	100.317	94.801	96.383	81.184
	0.933	1.767	0.767	2.333
225°	**1603.946**	**1423.805**	**1621.881**	**1287.952**
	108.613	111.744	118.995	84.401
	1.1	1.833	0.7	1.933
270°	**1600.83**	**1318.292**	**1660.996**	**1243.238**
	114.924	104.88	131.707	98.711
	0.767	1.533	433	1.7
315°	**1600.83**	**1232.019**	**1665.519**	**162.425**
	104.969	85.124	132.29	68.653
	0.6	1.367	0.767	1.433

8.3.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value	Power
Restriction	1	220227.555	220227.555	.668	.422	.123
Presentation	1	20130761.258	20130761.258	50.065	.000	1.000
Rotation	7	1801594.122	257370.589	4.930	.000	.996
Restriction * Presentation	1	100087.063	100087.063	.591	.450	.114
Restriction * Rotation	7	367253.195	52464.742	1.250	.279	.524
Presentation * Rotation	7	1982560.276	283222.897	6.339	.000	1.000
Restriction * Presentation * Rotation	7	252965.849	36137.978	.769	.614	.325

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value	Power
Restriction	1	.017	.017	.010	.919	.051
Presentation	1	199.838	199.838	5.203	.030	.597
Rotation	7	25.433	3.633	4.113	.000	.986
Restriction * Presentation	1	7.704	7.704	5.477	.026	.619
Restriction * Rotation	7	3.500	.500	1.038	.405	.442
Presentation * Rotation	7	17.746	2.535	2.451	.020	.863
Restriction * Presentation * Rotation	7	7.213	1.030	1.575	.144	.648

Chapter 9: Appendix 3

9.1 Statistical analysis for Experiment 5a

9.1.1. Table of means, standard error and mean errors for Experiment 5a by conditions.

	Restriction			
	Restricted		Unrestricted	
	Presentation			
Rotation	Mirrored	Unmirrored	Mirrored	Unmirrored
	1046.012	**871.722**	**1031.874**	**889.847**
0/360°	60.72	40.189	56.396	43.663
	1.4	0.433	1.167	0.8
	1159.129	**1051.556**	**1206.259**	**980.462**
45°	69.049	56.013	79.775	46.667
	1.367	0.867	1.067	0.9
	1308.86	**1110.779**	**1268.595**	**1171.497**
90°	86.699	63.806	85.64	75.637
	1.3	0.833	1.367	0.933
	1440.948	**1359.6**	**1600.531**	**1419.593**
135°	94.919	87.611	102.865	101.225
	1.267	1.967	1.467	1.733
	1638.188	**1585.874**	**1770.149**	**1568.932**
180°	120.02	112.28	141.726	112.824
	1.633	1.433	2.033	1.867
	1375.435	**1237.604**	**1359.488**	**1316.558**
225°	93.94	63.32	79.054	90.065
	1.233	1.533	1.267	1.367
	1337.577	**1181.326**	**1276.359**	**1130.321**
270°	107.045	81.985	85.786	72.166
	0.867	1.033	1.167	1.067
	1190.178	**1030.339**	**119.877**	**1049.874**
315°	88.52	71.156	80.133	63.825
	1.2	0.967	1.033	1.033

9.1.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value	Power
Restriction	1	72581.769	72581.769	.330	.571	.085
Presentation	1	3795447.790	3795447.790	32.770	.000	1.000
Rotation	7	31303782.250	4471968.893	46.947	.000	1.000
Restriction * Presentation	1	9836.767	9836.767	.385	.541	.091
Restriction * Rotation	7	405332.098	57904.585	2.154	.041	.803
Presentation * Rotation	7	98481.988	14068.855	.410	.895	.178
Restriction * Presentation * Rotation	7	389812.602	55687.515	1.633	.129	.662

i) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value	Power
Restriction	1	0.817	0.817	1.17	0.288	0.182
Presentation	1	4.004	4.004	1.028	0.319	0.165
Rotation	7	73.517	10.502	7.859	0.000	1.000
Restriction * Presentation	1	0.104	0.104	0.064	0.803	0.057
Restriction * Rotation	7	6.317	0.902	1.148	0.335	0.487
Presentation * Rotation	7	28.396	4.057	2.668	0.012	0.895
Restriction * Presentation * Rotation	7	6.096	0.871	1.168	0.323	0.496

9.2 Statistical analysis for Experiment 5b

9.2.1. Table of means, standard error and mean errors for Experiment 5b by conditions.

	Restriction			
	Restricted		Unrestricted	
	Presentation			
Rotation	Mirrored	Unmirrored	Mirrored	Unmirrored
0/360°	**1458.275**	**1218.042**	**1396.998**	**1224.581**
	104.79	72.549	76.885	58.801
	0.533	0.967	0.8	0.933
45°	**1460.179**	**1371.247**	**1437.735**	**1278.912**
	94.11	83.06	80.814	63.281
	0.533	0.967	1	1.2
90°	**1715.84**	**1560.039**	**1702.435**	**1429.964**
	77.07	112.999	98.21	90.476
	0.767	1.3	1.433	1.2
135°	**1747.03**	**1625.09**	**1744.97**	**1608.437**
	84.265	97.524	104.214	81.501
	1.3	1.967	1.533	1.567
180°	**1711.448**	**1609.763**	**1717.208**	**1508.345**
	113.171	126.316	97.667	83.656
	1.133	1.7	1.1	1.4
225°	**1604.152**	**1424.07**	**1544.405**	**1334.717**
	104.244	82.973	82.189	76.295
	1.1	1.533	1.1	1.4
270°	**1408.298**	**1250.87**	**1311.634**	**1176.865**
	105.547	69.331	74.898	86.922
	0.667	1.133	0.567	0.967
315°	**1318.583**	**1221.891**	**1304.803**	**1170.39**
	85.3943	68.956	84.85	70.522
	0.833	0.833	0.767	0.833

9.2.2. Analysis of variance tables for the analysis by participants

ii) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	**DF**	**SS**	**MS**	**F**	**P value**	**Power**
Restriction	1	536263.427	536263.427	1.476	.236	.215
Presentation	1	5369680.076	5369680.076	43.519	.000	1.000
Rotation	7	20456841.668	2922405.953	31.764	.000	1.000
Restriction * Presentation	1	66081.477	66081.477	1.879	.183	.261
Restriction * Rotation	7	125933.756	17990.537	.494	.838	.211
Presentation * Rotation	7	279036.898	39862.414	1.121	.352	.474
Restriction * Presentation * Rotation	7	178381.053	25483.008	.763	.619	.323

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value	Power
Restriction	1	.267	.267	.108	.745	.062
Presentation	1	21.004	21.004	7.486	.011	.753
Rotation	7	72.283	10.326	9.628	.000	1.000
Restriction * Presentation	1	5.104	5.104	2.894	.100	.377
Restriction * Rotation	7	7.967	1.138	1.053	.395	.448
Presentation * Rotation	7	4.096	.585	.516	.822	.221
Restriction * Presentation * Rotation	7	4.129	.590	.654	.711	.278

9.3 Statistical analysis for Experiment 6a

9.3.1. Table of means, standard error and mean errors for Experiment 6a by conditions.

	Restriction			
	Restricted		Unrestricted	
	Hand			
Rotation	Left	Right	Left	Right
0/360°	**820.524**	**727.59**	**800.811**	**736.699**
	60.972	38.126	46.723	39.222
	0.133	0.3	0.133	0.2
45°	**905.109**	**802.93**	**832.033**	**789.681**
	73.656	46.922	51.85	36.182
	0.267	0.233	0.3	0.233
90°	**951.26**	**988.102**	**935.38**	**874.556**
	88.776	112.265	67.04	49.929
	0.333	0.467	0.233	0.2
135°	**1193.822**	**1226.044**	**1084.608**	**1100.592**
	93.418	118.289	76.462	87.029
	1.433	1.133	0.433	0.633
180°	**1384.825**	**1375.376**	**1382.87**	**1402.376**
	87.875	103.294	106.898	104.552
	2.367	2.2	1.5	1.733
225°	**1256.552**	**1120.817**	**1246.171**	**1235.11**
	82.913	98.935	100.064	101.762
	1.667	1.533	1.167	1.367
270°	**1031.443**	**967.446**	**1001.654**	**947.926**
	64.05	81.284	64.598	65.262
	0.7	0.833	0.7	0.567
315°	**795.223**	**769.876**	**843.286**	**780.717**
	48.18	43.324	52.737	45.633
	0.267	0.13	0.1	0.167

9.3.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value	Power
Restriction	1	81236.911	81236.911	.922	.346	.152
Hand	1	300047.352	300047.352	3.305	.082	.415
Rotation	7	34300301.489	4900043.070	39.845	.000	1.000
Restriction * Hand	1	8035.339	8035.339	.396	.535	.093
Restriction * Rotation	7	523192.932	74741.847	1.392	.212	.579
Hand * Rotation	7	273011.623	39001.660	.949	.470	.402
Restriction * Hand * Rotation	7	192502.340	27500.334	1.184	.315	.499

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value	Power
Restriction	1	17.604	17.604	8.595	.007	.809
Hand	1	.038	.038	.040	.843	.054
Rotation	7	362.696	51.814	21.690	.000	1.000
Restriction * Hand	1	.704	.704	2.257	.144	.306
Restriction * Rotation	7	17.696	2.528	3.191	.003	.947
Hand * Rotation	7	.696	.099	.123	.997	.082
Restriction * Hand * Rotation	7	4.329	.618	1.202	.303	.510

9.4 Statistical analysis for Experiment 6b

9.4.1. Table of means, standard error and mean errors for Experiment 6b by conditions.

	Restriction			
	Restricted		Unrestricted	
	Hand			
Rotation	Left	Right	Left	Right
0/360°	**996.47** 48.391 0.4	**924.606** 48.854 0.167	**1018.376** 68.278 0.267	**914.56** 53.58 0.2
45°	**1121.982** 91.997 0.467	**887.175** 42.437 0.433	**1073.876** 72.775 0.233	**956.204** 65.424 0.3
90°	**1035.64** 65.704 0.367	**1052.702** 132.557 0.5	**1027.712** 50.17 0.3	**1007.525** 83.757 0.533
135°	**1143.891** 65.935 0.5	**1118.164** 74.499 0.933	**1228.67** 92.014 0.5	**1120.623** 58.604 0.767
180°	**1496.237** 78.699 1.967	**1305.472** 60.84 1.833	**1536.146** 106.96 1.567	**1396.303** 79.106 1.567
225°	**1369.72** 101.95 1.467	**1192.085** 77.458 1.033	**1288.841** 77.988 1.133	**1243.395** 76.316 1.067
270°	**1127.808** 73.335 0.767	**992.858** 43.978 0.967	**1130.402** 71.144 0.933	**1049.166** 70.849 0.567
315°	**1106.358** 79.393 0.4	**903.973** 41.095 0.167	**993.037** 63.757 0.167	**857.53** 33.72 0.2

9.4.2. Analysis of variance tables for the analysis by participants

i) ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value	Power
Restriction	1	3389.581	3389.581	.018	.895	.052
Hand	1	2357167.642	2357167.642	16.239	.001	.971
Rotation	7	18538808.967	2648401.281	27.488	.000	1.000
Restriction * Hand	1	54396.917	54396.917	1.609	.217	.229
Restriction * Rotation	7	344431.872	49204.553	1.052	.397	.444
Hand * Rotation	7	600738.465	85819.781	1.346	.232	.561
Restriction * Hand * Rotation	7	247588.121	35369.732	1.088	.374	.459

ii) ANOVA table for the analysis of participant error rates

Source	DF	SS	MS	F	P value	Power
Restriction	1	4.004	4.004	1.741	.197	.248
Hand	1	.038	.038	.026	.873	.053
Rotation	7	229.250	32.750	11.599	.000	1.000
Restriction * Hand	1	.150	.150	.240	.628	.076
Restriction * Rotation	7	2.013	.288	.425	.886	.185
Hand * Rotation	7	7.846	1.121	1.170	.321	.497
Restriction * Hand * Rotation	7	4.500	.643	1.042	.403	.444

Chapter 10: Appendix 4

10.1 Statistical analysis for Experiment 7a

10.1.1. Table of means, standard error and mean errors for Experiment 7a by conditions.

	Restriction			
	Restricted		Unrestricted	
	Reach			
Timing	Left	Right	Left	Right
1	**435.929**	**434.682**	**410.822**	**420.756**
	66.296	59.876	62.069	57.736
2	**435.735**	**444.036**	**428.29**	**456.602**
	61.067	55.279	51.456	61.014
3	**453.32**	**480.268**	**492.936**	**524.591**
	53.528	50.526	56.68	47.608

10.1.2. Analysis of variance tables for the analysis by participants

ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	**DF**	**SS**	**MS**	**F**	**P value**	**Power**
Restriction	1	6050.073	6050.073	.198	.660	.071
Reach	1	26093.894	26093.894	8.021	.008**	.781
Timing	2	243193.301	121596.650	5.596	.006**	.839
Restriction * Reach	1	3113.601	3113.601	1.404	.246	.208
Restriction * Timing	2	56269.540	28134.770	6.542	.003**	.894
Reach * Timing	2	9073.556	4536.778	1.988	.146	.394
Restriction * Reach * Timing	2	856.064	428.032	.148	.862	.072

10.2 Statistical analysis for Experiment 7b

10.2.1. Table of means, standard error and mean errors for Experiment 7b by conditions.

	Restriction			
	Restricted		Unrestricted	
	Reach			
Timing	Left	Right	Left	Right
1	**240.839**	**237.818**	**229.999**	**218.446**
	8.796	7.813	5.72	6.932
2	**268.41**	**274.977**	**292.085**	**294.271**
	9.861	9.955	9.188	10.429
3	**323.63**	**326.107**	**571.684**	**626.818**
	9.369	8.999	23.57	22.509

10.3.2. Analysis of variance tables for the analysis by participants

ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	DF	SS	MS	F	P value	Power
Restriction	1	788273.648	788273.648	84.596	.000	1.000
Reach	1	6705.860	6705.860	4.396	.045	.527
Timing	2	3514480.644	1757240.322	352.696	.000	1.000
Restriction * Reach	1	3949.078	3949.078	5.373	.028	.611
Restriction * Timing	2	1490998.998	745499.499	134.507	.000	1.000
Reach * Timing	2	20354.582	10177.291	8.914	.000	.966
Restriction * Reach * Timing	2	17536.885	8768.443	7.625	.001	.936

10.3 Statistical analysis for Experiment 7c

10.3.1. Table of means, standard error and mean errors for Experiment 7c by conditions.

	Restriction			
	Restricted		Unrestricted	
	Reach			
Timing	Left	Right	Left	Right
1	**539.422**	**546.699**	**478.81**	**504.225**
	56.695	54.847	51.031	50.154
2	**529.282**	**553.374**	**535.747**	**531.83**
	53.875	57.932	51.719	52.101
3	**546.70**	**638.846**	**638.849**	**681.472**
	55.927	60.225	42.84	40.079

10.3.2. Analysis of variance tables for the analysis by participants

ANOVA table on the participant means computed after removal of Response times more than 2 standard deviation from participant conditional means

Source	**DF**	**SS**	**MS**	**F**	**P value**	**Power**
Restriction	1	162.847	162.847	.005	.943	.051
Reach	1	64064.749	64064.749	7.040	.013	.726
Timing	2	880512.460	440256.230	34.447	.000	1.000
Restriction * Reach	1	2878.951	2878.951	.445	.510	.099
Restriction * Timing	2	166088.047	83044.023	8.182	.001	.951
Reach * Timing	2	34245.765	17122.883	5.084	.009	.800
Restriction * Reach * Timing	2	9615.751	4807.876	.971	.385	.210

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