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Visual and spatial processes underpinning intentional action

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VISUAL AND SPATIAL PROCESSES UNDERPINNING INTENTIONAL ACTION

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Hi ho, hi ho, it's off to Rome I go!

SUMMARY

This thesis is written as a collection of research papers in which the visual and spatial processes underpinning intentional action were investigated. The first half of the research explored the neural structures involved during visual imagery of movement. Moving a linear slide to a target was both performed and mentally rehearsed. Internal and external visual imagery groups performed mental rehearsal with, or without, concurrent secondary tasks to investigate interference effects, thereby allowing inferences to be made regarding the neural structures underpinning internal and external visual imagery. Studies 1 (a pilot) and 2 employed a concurrent finger sequence task. Analysis of constant error (study 2) provided some evidence of involvement of motor execution areas during imagery. Between group differences were not found, possibly due to a confound by kinaesthetic imagery. Study 3 presented one of two concurrent secondary tasks on a monitor: viewing a colour or visually tracking a slow moving dot. Rather than interfering, the stimuli facilitated performance. Viewing a colour resulted in smaller constant errors than mental rehearsal alone for both imagery groups. In addition, the External imagery group had smaller variable errors when performing imagery and a second task concurrently, compared to performing imagery alone. The second half of the thesis explored endpoint interference on distance reproduction. Participants made movements on a digitising tablet that were translated into movement on a monitor. In study 4 the home and target position on the monitor remained constant while initial position of the limb changed across trials. In study 5, changes in the home and target position were matched to changes in initial limb position. In study 6, the home and target position varied across trials while the initial position of the limb was constant. The results indicate movement bias based on previous endpoint and conflicting spatial information.

CHAPTER 1

GENERAL INTRODUCTION

Vision provides several types of information important for the planning and control of movement (Lee, 1978). According to Lee, visual information about objects (e.g., their identity, inherent characteristics) and their spatial relations are used in the planning of movements; vision also provides information about the location and movement of limbs relative to the rest of the body and the environment. Vision, therefore, allows for informed decisions to be made about what movement to make and how to make it (Lee, 1978).

In order to perform goal directed movements, an individual must code and translate spatial information into the appropriate motor commands needed to achieve the task goal (Abrams, Van Dillen, & Stemmon, 1994; Bock & Eckmiller, 1986). For example, when people perform rapid movements to specific locations in space (e.g., pointing, reaching and grasping an object, and/or moving a cursor on a computer monitor) they have to specify a number of spatial parameters. Among the spatial parameters specified are distance (Fitts, 1954), target orientation (Desmurget, Prablanc, Arzi, Rossetti, Paulignan, & Urquizar, 1996), and target location (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991). In addition, it is often useful to recognise the inherent characteristics of objects in the movement space. Factors such as object texture (Fikes, Klatzky, & Lederman, 1996), weight (Wing, 1996), and size (Jeannerod, Paulignan, MacKenzie, & Marteniuk, 1992) all affect how the motor system completes a goal directed movement.

Movements performed with vision have different kinematic profiles compared to those performed without vision of the environment. For example, when visual feedback of the movement environment is available, movements can be completed with a high degree of spatial precision. In reach and grasp tasks, ongoing visual feedback results in smaller maximum grip apertures than when reaching without vision (Wing, Turton, & Fraser, 1986). Ongoing vision also results in more accurate performance during manual aiming (Elliott & Calvert, 1990). Even periodic vision can enable highly accurate performance in one-handed ball catching, depending on the frequency and length of visual sampling (Elliott, Zuberec, & Milgram, 1994).

Goal directed movements may also be performed without vision. It is thought that these movements are guided by visual information contained in internal representations of the movement environment (cf., Elliott & Maraj; 1994). The lack of vision, however, results in modifications to the movement profile. For example, the kinematic profiles of movements performed without vision appear to demonstrate decreased spatial certainty. Wing et al. (1986) found reaching and grasping without vision required larger grip apertures than when vision was available, while Elliott and Madelena (1987) found that during manual aiming without vision, accuracy was decreased if the pre-movement delay was longer than 2 seconds. While these movements are less precise than when performed with vision of the environment, the ability to perform them suggests that we can utilise an internal representation of the external environment via visuo-spatial imagery (Elliott & Maraj, 1994; Chua & Weeks, 1994).

Structure of the Visuomotor System

Goodale and Milner (1992) have proposed that visual information is processed through two pathways in the cerebral cortex. The pathways allow the visual system to serve two different purposes: visuomotor control, and perception and recognition (Goodale & Milner, 1992; Milner & Goodale, 1995). The dorsal stream transverses an occipital-parietal route, while the ventral stream connects the occipital lobe to the temporal lobe (see Figure 1 for general locations). The dorsal visual stream has cells specifically involved in the computing and transforming of visual information to enable visuomotor control; cells responsible for encoding and 'interpreting' object properties and spatial relations are found within the ventral visual stream, thus allowing objects (including people) to be

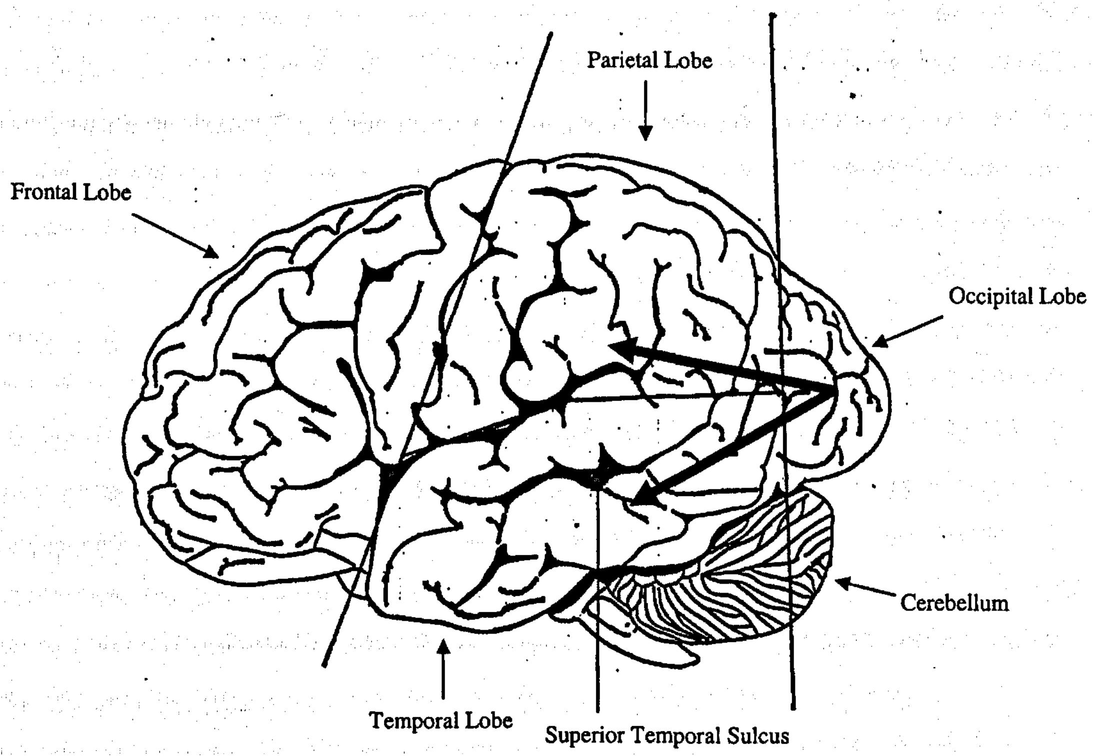

Figure 1. Illustration with location of lobes, cerebellum, and superior temporal sulcus (possible part of the third visual pathway). Large arrow from the occipital lobe to visual areas of the parietal lobe represent the dorsal visual stream. Large arrow from the occipital lobe to visual areas of the temporal lobe represent the ventral visual stream.

recognised (Milner & Goodale, 1995). Both streams are thought to process spatial and object information (e.g., size, texture) but do so using task specific algorithms (Goodale & Humphrey, 1998).

The presence of a distinction between task specific algorithms used for visuomotor control and task specific algorithms used for recognition is revealed by the ability of people with "blindsight" to accurately point to targets of which they have no conscious awareness (e.g., Weiskrantz, Warrington, Sanders, & Marshall, 1974; Perenin & Jeannerod, 1975). Blindsight occurs in people with damage to the primary visual area (located at the tip of the occipital lobe). Although they do not consciously perceive stimuli in the affected parts of the visual field, the stimuli are unconsciously processed and used to guide movements. This suggests that the algorithms for visuomotor control are accessible in blindsight, while those for conscious recognition of the target are not (Milner & Goodale, 1995).

The dorsal stream is thought to use viewer-centred (egocentric) coding (Goodale & Milner, 1992); egocentric coding of object position in relation to the observer does not require knowledge of object identity (Milner & Goodale, 1995). Multiple egocentric codes are associated with the head, eyes, arms etc. in relation to objects. "...Action upon the object requires that the location of the object and its particular disposition and motion with respect to the viewer is encoded (Goodale & Milner, 1992, p. 23)." These egocentric codes require constant updating as the individual interacts with the environment. Constant updating means that the storing of egocentric co-ordinates from one moment to the next is unlikely (Milner & Goodale, 1995). The dorsal stream functions concurrently, or "on-line", with action to guide our physical interactions with the environment (Milner & Goodale, 1995). On-line motor control is exemplified in target perturbation studies when "unconscious" prehensile corrections are made after a movement is initiated (e.g., Goodale, Pélisson, & Prablanc, 1986). Goodale et al. (1986) found that movement duration in trials where target position was perturbed did not differ from unperturbed trials, suggesting that corrections were made during the movement.

The ventral stream is thought to enable us to perceive and recognize that which is in the environment by using object-centred (allocentric) coding (Goodale & Milner, 1992); allocentric coding involves coding an object's spatial location in relation to the environment, in addition to the object's identity (Milner & Goodale, 1995). "... consistencies of shape, size, colour, lightness and location need to be maintained across different viewing conditions (Goodale & Milner, 1992, p. 23)". Milner and Goodale (1995) suggest that the ventral stream uses multiple stored codes (viewpoints), making it possible to "recognise" an object from any perspective even after many years. In addition, the cognitive manipulation of spatial information is likely to occur in the ventral stream as such tasks require allocentric coding of fixed landmarks and therefore require the use of a stored "map" (Milner & Goodale, 1995). Thus, information used in visual imagery may be provided by the ventral visual stream (Milner & Goodale, 1995).

Motor control is facilitated by the ventral stream through the provision of information regarding past experience (Milner & Goodale, 1995). The processing of spatial and object properties within the ventral stream enables it to provide a short-term memory of the visual scene that the motor system can substitute for concurrent visual feedback, therefore allowing the ventral stream to facilitate motor control through an "off-line" system (Milner & Goodale, 1995). For example, when people reach for objects after a movement delay of a few seconds, the ventral stream is thought to supply the dorsal stream with the relevant co-ordinates and object properties in order to run the on-line system. Thus, while the dorsal and ventral pathways are distinct, they are nevertheless interconnected and both streams play a role in the successful completion of goal directed movements (Milner & Goodale, 1995).

Milner and Goodale (1995) suggest that a third visual stream may have evolved, formed by a convergence between parts of the dorsal and ventral streams, and probably located in the superior temporal sulcus and the inferior aspect of the parietal lobe, located above the sulcus (see Figure 1). They suggest that this stream may contain a multimodal region, with both visual and tactile input[1]. The proposed function of this stream is to enable "higher order" visuospatial cognitive functions, including the conscious manipulation of imagery. Milner and Goodale suggest that the primary visual input into the third stream is ventral stream information about objects and spatial relations. The dorsal stream provides the egocentric coding and transformations, which originally evolved for movement guidance, that are applied to the information.

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[1] Their discussion was in relation to the visual and motor systems. No mention was made of including or excluding input from other senses into this area.

To summarise, according to Milner and Goodale (1995) visuomotor control is generally processed with egocentric coding in the dorsal visual stream. The ventral stream is thought by Milner and Goodale to use allocentric coding, and to affect motor control in an off-line manner via maintenance of internal representations of the external environment. These internal representations can be used to guide movements (cf., Elliott & Madalena, 1987). It should be noted that references to imagery by Milner & Goodale (1995) centred on visual and spatial images, not images involved in the mental rehearsal of movements. Milner (personal communication, 2 Oct. 2000) believes that the neuroscience data suggests that the parietal region has been implicated in the representational processes involved in visual imagery and visuospatial working memory, possibly involving the superior temporal sulcus. He could not suggest, however, any evidence regarding coding or neural structures that could be related to the distinction between the internal and external visual imagery used as mental rehearsal by athletes.

Forms of Imagery

Movement imagery has many uses, including the enhancement of performance in the absence of perceptual feedback (cf., Elliott & Maraj, 1994; Jeannerod, 1994), for mental rehearsal (cf., Feltz & Landers, 1983)[2], and to manipulate motivation and self-confidence (Paivio, 1985). An image can be based on information about the movement environment that is passively encoded and retained in memory (e.g., Elliott & Madalena, 1987), or actively generated from information already

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[2] According to Hardy, Jones and Gould (1996), mental rehearsal is a technique in which imagery is manipulated, and is thus distinguished from the mental process of imagery.

in memory (e.g., Roland & Friberg, 1985). Both visual and kinaesthetic imagery can be actively manipulated in order to affect changes to the human motor system (e.g., Hardy & Callow, 1999). Visual images used for mental rehearsal can be manipulated from two perspectives, internal and external. Internal visual images provide the perspective of a head mounted camera. External visual images have the perspective of a camera located on the other side of the room. An internal visual image can be described as viewer-based and therefore the internal representation of the external environment is probably egocentrically expressed. Sirigu and Duhamel (2001) stated that first-person imagery "allows a very direct mapping of the mental image onto one's own body schema (p. 912)". Their first-person imagery was presumably internal; the instructions were to "imagine a hand directly in front of your face and make a decision about finger location from your own viewpoint (p. 918)"; for example, "imagine looking at the back of your left hand, fingers pointing down ... is the little finger on the left or the right side? ... [answer: right] (p. 911)". In contrast, an external visual image of oneself may be object-centred (allocentrically drawn), as it is "environmentally referenced" rather than "viewer-centred"; the person watches him- or herself performing within the external environment. An external visual image may also be of someone else. Another type of imagery, referred to as kinaesthetic imagery, provides information about how movements feel and the proprioceptive localisation of body parts in relation to the rest of the body, and can be used in conjunction with either visual perspective (Hardy & Callow, 1999). Kinaesthetic imagery is, however, often mistakenly referred to as internal imagery (c.f., Hardy, 1997)

Minimal research has been performed on the neurophysiology of internal visual and external visual imagery (see Figure 2 for structural locations). Sirigu and Duhamel (2001) used a mental hand rotation task to compare performance in first–person and third–person visual imagery conditions. Participants were asked to imagine either looking at their own hand (see instructions described above) or imagine looking at the experimenter's hand (same instructions except the word "your" was replaced by "my", indicating the experimenter's hand) (Sigiru & Duhamel, 2001). Thus, the imagery instructions used in the experiment seem to correspond to the definitions of internal visual and external (of someone else; "treat the hand not as one's own body part but as an external object whose orientation in space can be evoked" [Sirigu & Duhamel, 2001, p. 911]) visual imagery, respectively. The performance of healthy control participants was compared to two patients. One patient had an inferior temporal lesion and was unable to visualise faces or object shapes. The second patient had an inferior parietal (generally considered areas 39 and 40; see Figure 2) lesion and exhibited limb apraxia (impairment of fine movement). Through comparison of response latencies and error rates of the patient's performances to the control participants, it was determined that first-person imagery involved inferior parietal areas associated with the motor system, while the third-person imagery involved the inferior temporal region. The third-person imagery results indicated that "imagining a hand construed as somebody else's is best achieved through a nonmotor route (p. 912)".

Deiber, Ibañez, Honda, Sadato, Raman and Hallett (1998) asked participants to imagine simple finger movements (abduction and adduction) of their own fingers with external (of self) visual imagery. In contrast to Sirigu and Duhamel's findings of the involvement of the inferior temporal lobe during external (of someone else) visual imagery, Deiber et al. recorded activation of the inferior parietal cortex (areas 39 and 40), along with activation of premotor, supplementary motor, cingulate (area 32), and dorsalateral prefrontal areas 9 and 46, during external (of self) imagery. Thus, it appears that external visual imagery of self is processed differently from external visual imagery of someone else. This research was identified after the imagery studies in the present thesis were designed and the majority of the data collected; thus, the findings were not taken into account when the external imagery hypotheses were first specified.

Internal visual and external visual imagery perspectives appear to affect the motor system in different ways. For example, White and Hardy (1995) identified a speed/ accuracy trade-off. Participants were assigned to either an internal visual or external visual imagery condition. Participants practiced a wheelchair slalom task, using imagery before each trial. They were then asked to return one week later to perform a transfer test on a new course. The internal visual imagery group performed the transfer test more accurately than the external visual imagery group, while the external visual imagery group navigated the course faster than the internal imagery group.

On a rhythmic gymnastics task, White and Hardy (1995) found that after one week, participants in an external imagery group could correctly recall more of a previously learned routine than could an internal imagery group. Hardy (1997) suggested that internal visual imagery may be beneficial in tasks where responses

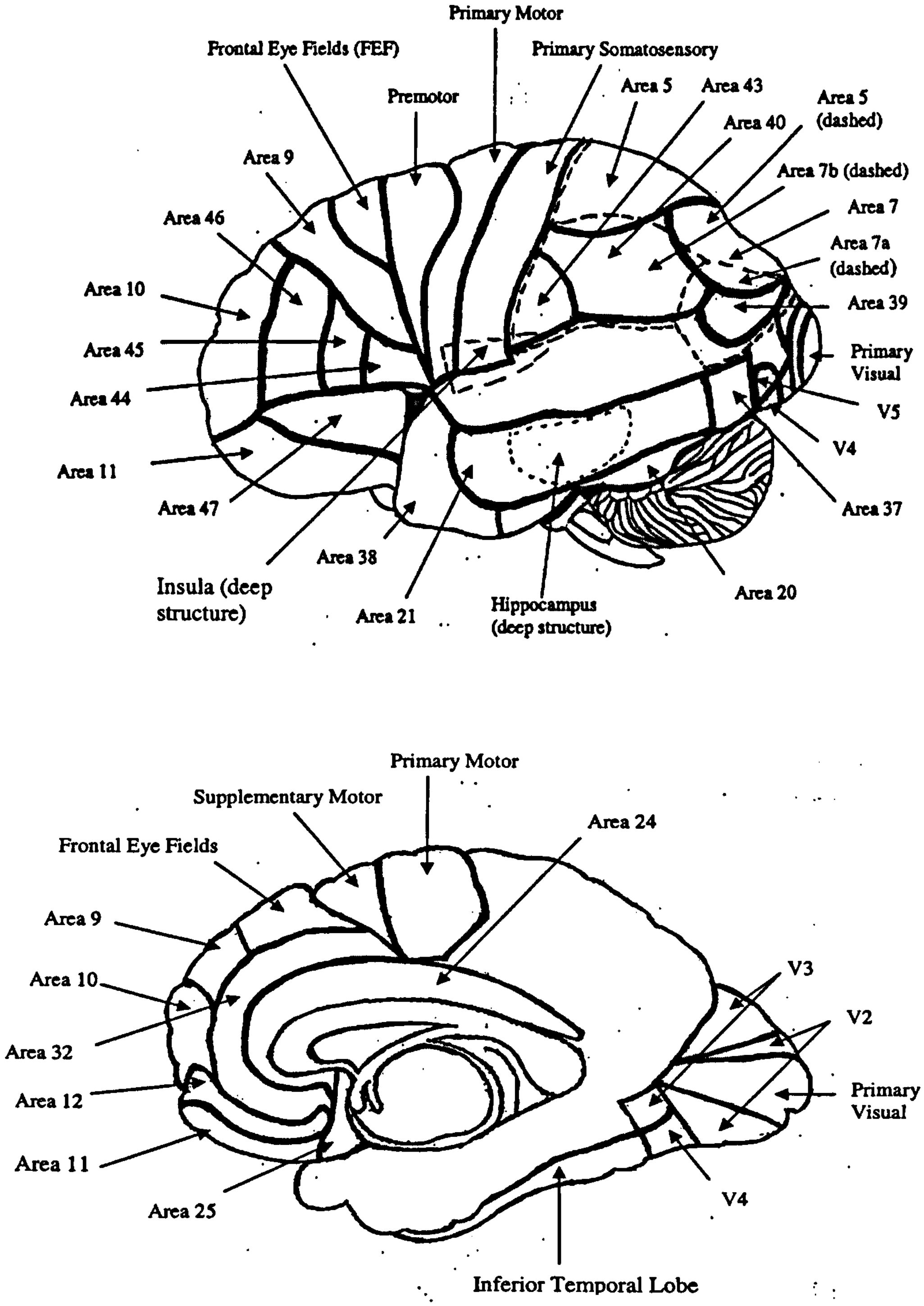

Figure 2. Lateral view in upper panel, medial in lower panel. Positional approximations based on Kolb and Whishaw (1996) and Passingham (1993). Notations based on localization by Brodmann area, except areas 5, 7a and 7b (dashed) localized by Felleman and van Essen area. Region 7a also contains VIP, LIP and MST mentioned in this thesis.

must be timed in relation to environmental cues, while external visual imagery may be more beneficial than internal visual imagery to the learning of tasks in which correct form is important for successful completion. Hardy and Callow (1999) conducted an experiment in which experienced karatists learned a new kata sequence consisting of 52 movements. Those participants assigned to an external visual imagery group performed the kata better after 5 weeks of practice, and in a retention test 2 weeks later, than did those assigned to an internal imagery group. In a second study, using sport science students, external visual imagery led to better performance on a gymnastics floor routine then did internal visual imagery. In their third study, experienced rock climbers performed a newly learned "boulder problem". The external imagery group was able to complete more moves before falling off the climbing wall than the internal imagery group. Taken as a whole, the Hardy and Callow studies suggest that external visual imagery provides useful information regarding the form of movements.

In the past, the term "motor imagery" has been used rather ambiguously in the literature. For example, the instructions to 'imagine picking up an object' (e.g., Grafton, Arbib, Fadiga, & Rissolatti, 1996) does not indicate whether the person should use a visual or kinaesthetic image, or both. In addition, visual perspective is not specified. It is sometimes argued (e.g., Jeannerod, 1994) that motor imagery is primarily kinaesthetic. The evidence suggests, however, that any imagery of physical movement produces activation of neural structures within the motor system and is therefore subsumed by the concept of motor imagery. For example, Deiber et al. (1998) recorded activation of structures in the (pre) supplementary motor and premotor areas when participants formed visuospatial images of simple finger movements (see Figure 2 for general locations of structures). Even imagery of body parts (e.g., mental rotation of hands) produces activation of the primary motor and premotor areas (e.g., Kosslyn, DiGirolamo, Thompson, & Alpert, 1998). Thus, motor imagery can involve the manipulation of visual and/*or* kinaesthetic imagery.

The literature presented above has reported that the visual system manipulates both visual (object) and spatial information. Visual imagery is also manipulated in the visual system. By convention, visual imagery used for mental rehearsal is labeled 'visual', however it is in effect 'visuospatial'. The images are visual in nature and utilise parts of the brain associated with vision. Thus, as with vision itself, visuospatial imagery can be subdivided into parts that are specifically visual (e.g., processing colour) and parts that are spatial (Farah, Hammond, Levine, & Calvanio, 1988). Using this subdivision, visual (object) imagery allows us to recognise imagined objects and their inherent characteristics (e.g., texture, relative size). Spatial imagery allows us to manipulate the spatial properties of the image (e.g., distances, orientations), without regard to the identity of the objects in the image (Shepard, 1982).

The identification of cortical structures involved in visual and spatial imagery has primarily been based on studies of patients with lesions or head injuries. Damage is rarely confined to a discrete area, or to a population of neurons responsible for only one type of processing (e.g., line orientation). Thus, while there is a general understanding of where different types of images are processed, the specifics are incomplete. It appears that visual imagery is processed in structures within the ventral stream and that spatial imagery is processed in structures within the dorsal stream (Farah, 1988). However, as spatial imagery can also be performed by the congenitally blind (e.g., Carpenter & Eisenberg, 1978), it seems unlikely that *all* spatial imagery occurs in the dorsal visual stream. Carpenter and Eisenberg suggest that because the congenitally blind have no long-term memory of visual experiences with which to generate a visual image, the fact that they can perform spatial tasks (e.g., mental rotation) indicates that spatial imagery is not purely visual. An alternative, or additional, location for the processing of spatial images may be the border area between the dorsal and ventral visual streams that Milner and Goodale (1995) proposed has inputs from the visual and tactile modalities.

To summarise, there is evidence that visual and spatial imagery involves structures in the visual system, and that internal and external visual imagery can lead to changes in the motor system via mental rehearsal. It was considered whether the brain structures involved in internal and external visual imagery of movement could be localised in the dorsal (egocentrically coded) and ventral (allocentrically coded) visual streams, respectively. This question formed the basis of the research reported in Chapters 2 and 3. Research exploring the relation between visual imagery and the motor system is presented in the next two subsections.

Neural Activation by Visual Imagery of Movement and Object Motion. Apparent motion is induced when two objects are presented in close temporal succession, giving the impression that one object has moved to a second location. In a study by Geobel, Khorram-Sefat, Muckli, Hacker and Singer (1998), both apparent motion and imagery of previously seen apparent motion activated dorsal visual areas V5 and MST. Activation during imagery of the superior and inferior parietal lobes was interpreted as activation of dorsal visual areas VIP, LIP and 7a (see Figure 2 for general locations of structures). In addition, dorsolateral prefrontal areas 9 and 46 (working memory), and the frontal eye fields (area 8) were found to have higher activation levels during imagery of apparent motion. Based on the overall pattern of activation during imagery, the use of spatial attention and spatial working memory processes was inferred.

A rather broad category of task involves mentally traversing distances. In mental map scanning tasks, a person is asked to memorise locations on a map, and then to scan between points on the map. Thus, the task involves locating landmarks relative to one another on the mental map. When people mentally scan between points on a memorised map, scanning times increase linearly with distances on the map (Kosslyn, Ball, & Reiser, 1978), much as would be found for scanning a real map. Mental map scanning activates visual and motor areas (superior occipital lobe [unspecified area within the dorsal visual pathway], supplementary motor area, and cerebellum) (Mellet, Tzourio, Denis, & Mazoyer, 1995).

Another task involving the traversing of distances is mental navigation along memorised routes. Roland and Friberg (1985) instructed people to imagine walking from their own front door, down the street, and making alternate right/ left turns at corners. The task led to activation of visual areas (superior occipital, posterior parietal and posterior inferior temporal areas [specifics not provided]). The pattern of activation was interpreted by Roland and Friberg as involving the retrieval of the memories (particularly the temporal activation) and the processing of spatial information (particularly the parietal activation). Ghaëm, Mellet, Crivello, Tzourio, Mazoyer, Berthoz and Denis (1997) asked participants to physically walk a route several times. During the walk they were told to memorise visual landmarks, changes in orientation that occurred, and changes in gait. When later asked to use visual and kinaesthetic imagery to mentally navigate between landmarks along the walk, two networks were activated. Specific to mental navigation, dorsal visual area 7a (precuneus), the supplementary motor area, part of the hippocampus (area 28) and insula were activated. The involvement of the insula was possibly due to evocation of body position, as its activation is related to the somatosensory system in non-human primates (Ghaëm et al., 1997). Activation in the second network, interpreted by Ghaëm et al. as indicating the employment of long-term memories, included the cingulate, dorsolateral prefrontal, and middle and inferior temporal (including hippocampus; other areas unspecified) areas. Thus, mentally traversing distances tends to activate areas involved in the recall of memories, in addition to visual and motor areas.

Mental rotation is another common imagery task. Mental rotation studies provide people with two objects at different angles and ask them to decide if the objects are the same or different. Shepard and Metzler (1971) conducted a now classic study illustrating that the time required to recognise whether or not two drawings are the same increases linearly with the angular difference of the drawing orientations. Cohen, Kosslyn, Breiter, DiGirolamo, Thompson, Anderson, Bookheimer, Rosen and Belliveau (1996) mapped the brain activation of a rotation and a no rotation condition using the original Shepard and Metzler figures. The data showed that mental rotation per se activated the frontal eye fields (area 8) and the dorsal visual stream (areas 7a, 7b, 39 and V5) in at least seven out of eight participants. In addition, about half of the participants also showed activation of the premotor, primary somatosensory, and dorsolateral prefrontal areas 9 and 46 during mental rotation.

Mental rotation of hand shapes also takes longer as the angular difference between the stimuli increases (Cooper & Shepard, 1975). However, the neural activation produced by the mental rotation of pictures of hands appears to differ from that of objects (Kosslyn et al., 1998). Kosslyn et al. found that mentally rotating hands and objects activated superior parietal area 7 in the dorsal stream. Rotation of hands additionally activated the primary visual area, dorsolateral prefrontal area 9, and the premotor and primary motor cortices. Ganis, Keenan, Kosslyn and Pascual-Leone (2000) isolated activation in the primary motor cortex to the hand representation during mental rotation of hands. Primary motor involvement is a notable finding as participants did not make any noticeable hand movements in either study, and the primary motor cortex has traditionally been considered a motor execution area. Kawamichi, Kikuchi, Endo, Takeda and Yoshizawa (1998) recorded the temporal succession of activation and found mental rotation of hands activated the visual cortex, followed by the inferior parietal (specific locations not provided) and premotor cortices. Thus, mental rotation leads to activation of visual and motor areas, as well as areas involved in working memory (e.g., dorsolateral prefrontal area 9). Unlike mentally traversing distances, however, there is no evidence of involvement of areas associated with the recall of long-term memories.

Some imagery research has been carried out on object-directed tasks, e.g., imagined grasping. Grafton et al. (1996) found that when participants imagined performing a precision grasp, structures were activated in the dorsal visual stream (area 40), motor areas (supplementary and premotor cortices; cerebellum) and the inferior frontal region (area 44 [interpreted by Grafton et al. as involvement in object-related grasping]). These areas were similar, but not identical to those recorded during observation of a precision grasp: different parts of the cerebellum were active and inferior prefrontal area 45 [interpreted function was action recognition] was active instead of area 44. In a separate study, imagined grasping of virtual three-dimensional cylinders and spheres with one's own hand led to an activation profile that was interpreted as indicating motor preparation and planning: dorsal visual area 40, motor areas (frontal eye fields [area 8]; premotor cortex; parts of the cerebellum), dorsolateral prefrontal areas 9 and 46, and the cingulate (areas 24 and 32) (Decety, Perani, Jeannerod, Bettinardi, Tadary, Woods, Mazziotta, & Fazio, 1994). Although there was a lack of supplementary motor activation during imagined grasping in the Decety et al. study, the "most likely interpretation for this discrepancy is that the virtual objects (in Decety et al., 1994) … were insufficient to evoke a motor image such as to activate (supplementary motor) areas (Grafton et al., 1996, p. 109)". When instructed to observe watching a virtual hand grasping ("as if it were their own hand" [Decety et al., 1994, p. 600]) the same virtual objects, visual areas (including temporal area 37 and inferior parietal area 39), the cingulate cortex (area 24 and 32), and the cerebellum, were activated. Thus, imagined action and observed action lead to different activation profiles.

To summarise, the neural structures involved during imagined movement and motion are similar to those involved in real movement, including the frontal eye fields, cerebellum, premotor, supplementary motor, and primary motor areas. The literature indicates that structures in the dorsal stream activated by visual imagery extend beyond the inferior parietal area. In addition, imagery involving the manipulation of spatial parameters appears to be governed by the same constraints as are applied to real motion (see also Shepard, 1984). As imagined angular and linear distances increase, response times increase in mental rotation and scanning tasks respectively. These results suggest that the processing of imagined movement has a similar duration and number of steps, as does the processing involved in real movement.

Functional Equivalence in Performance Resulting from Real and Imagined Movements. The term "functional equivalence" indicates a level of equality between the effects produced by observed objects and events, and imagined objects and events (cf., Finke, 1980). The functional equivalence of movement bias in imaged and executed movements has been reported in several studies. For example, Finke (1979) showed that pointing errors induced by prisms and imagery were similar. The visual-motor aftereffects caused by prism adaptation were proportional regardless of whether participants imagined or observed their errors during adaptation. Using a linear reproduction task, Johnson (1982) found criterion distance reproduction was biased by real and imagined movements to different distances. In addition, imagined and real movement speeds biased the recall of speed in a sequential motor task (Boschker, Bakker, & Reitberg, 2000).

Georgopoulos and Massey (1987) asked participants to move an arm manipulandum to specific angles. The results suggested that participants used mental rotation to plan the movement responses. Similar to other mental rotation research, reaction time increased linearly with increasing angular movement amplitude. Furthermore, when an amplitude-accuracy (achieving the correct angle) analysis was performed, it was found that the increasing reaction time was a linear function of task difficulty (Fitt's law). This suggests that the imagined movements were manipulated in accordance with the laws that govern actual movement. Further evidence for the application of Fitt's law to imagined movement has been revealed, along with evidence that maximal imaged and executed movement speeds are approximately equal (Sigiru, Duhamel, Cohen, Pillon, Dubois, & Agid, 1996).

In summary, the evidence in this section suggests that imagined performance is functionally equivalent to actual performance. While the absence of kinaesthetic imagery in the studies mentioned above and in the previous section cannot be guaranteed, every effort was made to carefully scrutinize the methodologies reported for description of kinaesthetic imagery. Thus, the literature contained in this and the previous section can be considered as evidence that visual imagery interacts with the motor system.

Coding of Spatial Information

The types of physical movement that participants made in the studies contained in this thesis are linear aiming movements. Successful completion of such movements requires the participant to accurately code the distance to move and/or the precise location of the target. There is a controversy in the motor control literature regarding whether distance or location information is coded, or both. Evidence, presented below, suggests that these two types of spatial information are coded in parallel and exert an influence on subsequent movement, even when the spatial coding is based on unreliable information. That is to say, spatial information that would be advantageous to ignore exerts an influence nevertheless.

Evidence from Short-Term Memory Studies. In a distance reproduction task, a person is presented with a criterion movement. After a delay period, the person is asked to reproduce the distance of the criterion movement. The start position is typically shifted forward or backward from the original start location. Walsh and Russell (1979) found that when the start location was shifted toward the endpoint of the previous trial, participants undershot the correct distance. When the start location was shifted away from the endpoint of the previous trial, participants overshot the correct distance. The same pattern of bias was found regardless of the pre-movement delay (5 or 30 seconds). Thus, it appears that previous endpoint location was encoded, retained and retrieved even though the relevant information needed to complete the task was distance information.

In a location reproduction task, a person is presented a criterion movement and is then asked to reproduce the endpoint of the criterion movement after a delay period. The start position is typically shifted forward or backward from the original start location. Walsh and Russell (1979) found that when the start location was moved backward, participants undershoot the target location. When the start location was moved forward, the target was overshot. Thus, it appears that distance information is being encoded, retained and retrieved even though relevant information needed to complete the task was target location.

Walsh (1981) found that at short distances (<16 cm) shifts in the start position resulted in distance cues interfering with endpoint reproduction. In contrast, the effect of endpoint cues on distance reproduction was negligible. Wrisberg and Winter (1985) found similar results for endpoint reproduction (see also Wrisberg, Millslagle, & Schliesman, 1987). Wrisberg and Winter showed that shifts in start location strongly influenced endpoint reproduction at movement distances up to 30 cm. The effect was weaker for medium length movements (50 cm) and negligible at 80 cm. Endpoint interference in distance reproduction has been reported for 25 cm movements (Walsh & Russell, 1979) and 20-30 cm movements (Imanaka & Abernethy, 1992b). Thus, movement lengths of 16 – 30 cm have been found to exhibit a high degree of interference, with endpoint biasing distance reproduction and distance biasing endpoint reproduction (cf., Imanaka, Abernethy, & Quek, 1998).

The inability of people to ignore unreliable spatial information does not appear to be related to the vividness of the information retained in short-term memory.

Walsh, Russell and Imanaka (1980) tested whether people who had rated themselves high-vividness imagers differed in performance from those who rated their imagery as low-vividness. Movement distances of 30 – 40 cm were used. Regardless of reported imagery vividness (high or low), the typical results were replicated. Incorrect endpoint information led to inaccurate recall of distance, while incorrect distance information led to inaccurate recall of endpoint. These results held even when the correct spatial cue (distance and endpoint, respectively) was actively rehearsed for 30 seconds.

***The Effect of Cognitive Factors*.** Movement pre-selection (participant determines endpoint/ distance of criterion movement) appears to be a factor in the accuracy of reproduction tasks because of the information it provides. For example, Roy and Diewert (1978) found that the accurate coding of movement distance was enhanced by pre-selection of movement distance. Participants pre-selected the distance to move by sliding the handle of a linear slide 60 cm and then sliding it a second distance, which the participant thought was one half the original distance. Similar results were found when the experimenter specified the required distance, but only if prior information about the relation between the criterion distance and reproduction distance was provided. That is, if participants knew that the reproduction distance was one half of the criterion distance then their accuracy was equivalent to the pre-selected condition. If the participants had no prior knowledge, then the usual pattern of bias was found. Thus, it appears that the act of pre-selecting provided the participant with information about where to terminate the movement, prior to the initiation of the reproduction task.

Imanaka and Abernethy (1992b) further investigated the influence of prior knowledge on location and distance reproduction tasks. In a series of three studies, participants pre-selected criterion movements of 20-30 cm. In a location reproduction study Imanaka and Abernethy tested whether *unattended* distance cues, or distance information in general, interferes with accurate recall of location. Participants in the end-only condition were told to focus on the end location and to ignore all other cues. These participants were told that the start of the criterion and reproduction movements was not fixed. In contrast, participants in the start-end condition were provided with precise information that the start position would change 0, 2 or 4 cm in either direction from the start of the criterion movement. The start-end group did not show undershooting and overshooting, but the end-only group did, indicating that the usual response bias was caused by unattended distance cues rather than distance information itself.

The second and third studies performed by Imanaka and Abernethy (1992b) used distance reproduction tasks. In study 2, participants were assigned to use one of three strategies. Participants either tried to encode distance by mentally counting while moving at a constant velocity, or were told to image a movement (or ruler) 20-30 cm in length. In both conditions, movement bias was produced by unattended location information. In contrast, participants in a general location condition were told to remember the start and end location of the criterion movement and that they should account for changes in the start position during distance reproduction. Participants in this group showed a decrease in movement bias. In study 3, the general location group was additionally provided body-centred reference information. That is, instructions regarding the pre-selection of the criterion movement included that the end of the movement was in line with the participant's right armpit. In this study, movement bias in the general location group was further reduced, and was similar to the explicit location information condition. In the explicit location condition participants had specific details about the start and end of the criterion movement, shifts in the start location and the relation to body based coordinates. Both studies showed that actively attending to information regarding start and end locations diminished movement bias during distance reproduction, particularly if body-based referencing was provided.

To summarise, past research has shown that shifts in initial limb position can result in movement bias in both distance and endpoint reproduction tasks. This result has generally been attributed to the retention of the previous movement endpoint. The finding that actively attending to spatial information can decrease the interference effect suggests the involvement of abstract memory codes (e.g., Imanaka & Abernethy, 1992b). In addition, endpoint coding has been accounted for by equilibrium point models (e.g., Feldman, 1986), which propose that final limb position is based on the length-tension relationship between the agonist and antagonist muscles. The interference effect and the influence of conflicting spatial information within a trial formed the basis of the research presented in Chapter 4.

Overview of the Thesis

This thesis contains six studies exploring the visual and spatial processes underpinning intentional action. In line with the School of Sport, Health and Exercise Sciences policy, the studies have been written to stand as discrete papers.

Study 2 has been presented at an international sport psychology conference, study 3 at an international cognitive neuroscience conference, and studies 4, 5, and 6 were combined for presentation at an international motor control conference. Study 3 is in preparation for submission as a paper. A paper based on the combination of studies 4, 5 and 6 is in press (Experimental Brain Research). The general introduction and discussion serve as a link between the studies. The general introduction provides an overview of the visual system and how visual information affects the human motor system. Discussion of the structure and functions of the visual system is followed by an introduction to the imagery and spatial coding research. The section on imagery research presents the forms of imagery, neural activation during visual imagery of movement and object motion, and functional equivalence in performance resulting from real and imagined movements. The section on coding spatial information includes evidence from short-term memory studies and the effect of cognitive factors. The general discussion contains a summary of the main findings, theoretical considerations, strengths of the research programme, limitations of the current research programme and future directions, and other future directions of research.

The Research Programme

The first half of the research programme (chapters 2 and 3) entailed three studies which considered the neural structures involved in visual imagery of movement. These studies were highly exploratory in nature. Studies 1 and 2, reported in Chapter 2 , attempted to determine if motor areas were differentially involved in internal and external visual imagery. This was accomplished by asking participants to mentally rehearse using imagery alone or to mentally rehearse while performing a finger sequence task. Two studies were conducted, as study 1 revealed a number of methodological issues that needed to be addressed. Study 3, presented in Chapter 3, attempted to determine if colour and motion processing areas within the visual system were differentially involved in internal and external visual imagery. Participants performed imagery alone, while viewing motion, or while viewing colours.

The second half of the research programme (chapter 4) involved three studies (studies 4, 5 and 6) examining distance and endpoint coding during a video aiming task. This task involved participants performing a distance reproduction task on a digital tablet, which was then translated into movement of a cursor on a monitor. Thus, this task differed from the distance versus endpoint coding studies described earlier in that the motor and visual spaces were de-coupled, allowing the systematic manipulation of one or both sensory spaces. In study 4 the home and target positions viewed on the monitor stayed constant while the start position of the hand varied from trial to trial. In study 5, shifts in the start and end position of the criterion displayed on the monitor were synchronised to shifts in the start position of the hand. In study 6, the start and end position of the criterion displayed on the monitor varied from trial to trial while the start position of the hand remained constant.

Summary

The thesis addressed the following research questions:

1. Can we find evidence that internal and external visual imagery are manipulated within structures of the dorsal and ventral visual streams, respectively, using an interference paradigm?
    A. Will the more direct connections between the dorsal visual stream and motor areas mean that a secondary motor task will interfere more with internal imagery than with external imagery, as would be predicted if internal imagery is manipulated in the dorsal visual stream?
    B. Will a secondary visual task using the dorsal stream affect internal imagery more than external imagery, as would be predicted if internal imagery is manipulated in the dorsal visual stream?
    C. Will a secondary visual task using the ventral stream interfere with external imagery more than internal imagery, as would be predicted if external imagery is manipulated in the ventral visual stream?
2. What is the effect on a distance reproduction task of conflicting visual and motor sensory information?

CHAPTER 2

FINGER SEQUENCING AND INTERFERENCE WITH VISUAL IMAGERY OF MOVEMENT[3]

Abstract

Two studies investigated the differential involvement of the motor cortex in internal visual and external visual imagery of movement. A concurrent secondary motor task was used in an attempt to demonstrate interference, indicating that structures in the motor system are involved in the imagery. Study 1 served as a pilot, which identified several methodological issues to consider. In study 2 participants (*N* = 24) were randomly assigned to either an internal visual or external visual imagery group. Actual movement involved sliding a handle along a track way to one of three targets (461 mm, 530, 604) from the start position. Movements alternated with a second task in three blocked conditions: mental rehearsal (Reh.), mental rehearsal while concurrently finger sequencing (Seq.), and mental mathematics (Math.). Initial analysis of absolute constant error and variable error showed no effects. Cross-referencing with the post-experimental questionnaire, it was determined that absolute constant error was possibly confounded by kinaesthetic imagery. The Seq. and Reh. data were divided into "used" and "did not use" kinaesthetic imagery. A secondary analysis, using unweighted means, confirmed that kinaesthetic imagery affected Reh. and Seq. differently. Further analyses indicated that visual plus kinaesthetic imagery reduced errors, compared to visual imagery alone, in Seq. Participants who did

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[3] Experiment 1 is included in this chapter as it was a complete study conducted for this thesis. For submission as a paper, Experiment 1 would be summarised as a pilot work and only Experiment 2 would be reported as a full study. The research reported in Experiment 2 was presented at the Tenth World Congress of Sport Psychology in 2001.

not use kinaesthetic imagery in either condition had larger errors in Seq. The secondary analyses were interpreted as support for the hypothesis that visual imagery of movement operates in the motor cortex, although differential involvement in internal and external visual imagery was not ascertained.

Introduction

The human motor system can be affected by visual imagery of movement (e.g., Budney, Murphy, & Wooolfolk; White & Hardy, 1995). Two forms of visual imagery may be used: internal and external (e.g., Hardy & Callow, 1999). An internal visual image seems to be egocentrically coded (cf., Sirigu & Duhamel, 2001). As a person imagines interacting with the external environment their imagined body-centred spatial map changes accordingly, suggesting that egocentric codes are employed (cf., Milner & Goodale, 1995). In contrast, an external visual image of oneself seems to be allocentrically coded. Allocentric coding uses points in the environment to code the spatial relations between objects without reference to the location of the viewer (Dijkerman, Milner, & Carey, 1998); the stability of the object information enables recognition from any angle (Milner & Goodale, 1995). The proposition that external visual imagery uses allocentric coding is based on the lack of body-centred coding, and the ability to view oneself from any angle, that characterise external imagery. Within the visual system, egocentric and allocentric coding are thought to occur in the dorsal (occipital-parietal) and ventral (occipital-temporal) streams, respectively (see Figure 3) (Milner & Goodale, 1995). From this it may be hypothesised that internal and external visual imagery operate in structures within the dorsal and ventral streams, respectively.

Previous research has shown that visual imagery (e.g., mental comparison of two objects) and visual perception use the same neural structures (Farah, Péronnet, Gonon, & Girard, 1988; Farah, Hammond, Levine, & Calvanio, 1988). In addition, imagining and performing movements activate many of the same parts of the brain (e.g., Stephan, Fink, Passingham, Silbersweig, Ceballos-Baumann, Frith, & Frackowiak, 1995). The current research was part of a programme that used behavioural tasks to investigate the neural structures underlying visual imagery of movement used for mental rehearsal.

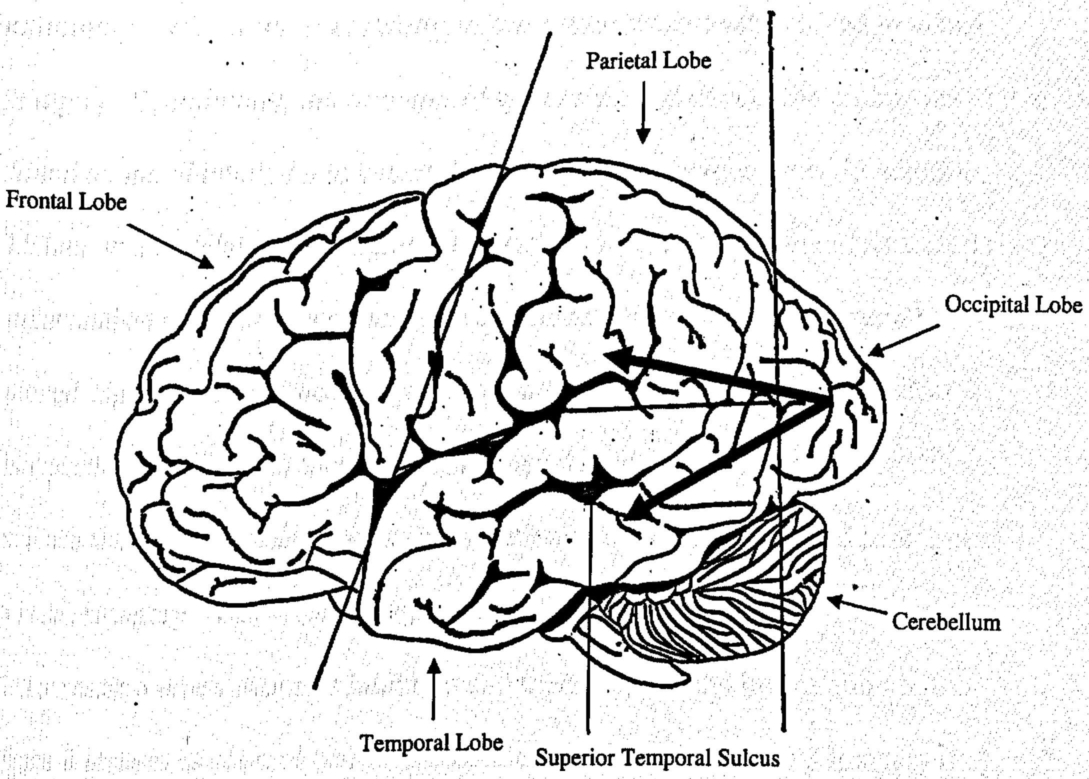

Figure 3. Illustration with location of lobes, cerebellum, and superior temporal sulcus (possible part of the third visual pathway). Large arrow from the occipital lobe to visual areas of the parietal lobe represent the dorsal visual stream. Large arrow from the occipital lobe to visual areas of the temporal lobe represent the ventral visual stream. This figure was also presented in Chapter 1 as Figure 1.

It was hypothesised that internal visual imagery operates within dorsal stream structures and external visual imagery within ventral stream structures. This hypothesis imposes the structure of Milner & Goodale's (1995) theory of visual system functions onto the investigation of visual imagery of movement. This link is admittedly tenuous, the primary problem being that internal visual imagery is not an equivalent to on-line visuomotor control (D. Milner, personal communication, 2 Oct. 2000); Milner and Goodale propose that on-line visuomotor control is the primary function of the dorsal visual stream. Nevertheless, it remains that several aspects of Milner and Goodale's theory are extremely useful when speculating on the neural structures involved in visual imagery. Specifically, the concepts of egocentric and allocentric coding are viable descriptions of internal and external visual imagery perspectives. In addition, Milner and Goodale have suggested that, from moment to moment, egocentric information changes as a person moves, and therefore the dorsal stream relies on stored algorithms or "knowledge" of the normal relations between physical properties. Thus, even though internal visual imagery is not on-line, structures within the dorsal stream contain information that would be useful during internal visual imagery. The ventral stream, according to Milner and Goodale, stores information when action is inhibited and then supplies the information to the dorsal stream as soon as action is possible again. External visual imagery may therefore affect the motor system indirectly by a similar mechanism.

The visual system is connected to the motor system via dorsal prefrontal area 46 (executive functions) (Passingham, 1993) (consult Figure 4 for location of structures). The dorsal visual stream has numerous connections to area 46; in contrast, the ventral visual stream connects to ventral prefrontal areas 11 and 12, and has only light connections to area 46 (Passingham, 1993). Areas 11 and 12 are involved in emotional responses (Kolb & Whishaw, 1996). Connections of the ventral visual stream to motor areas would almost certainly be via the

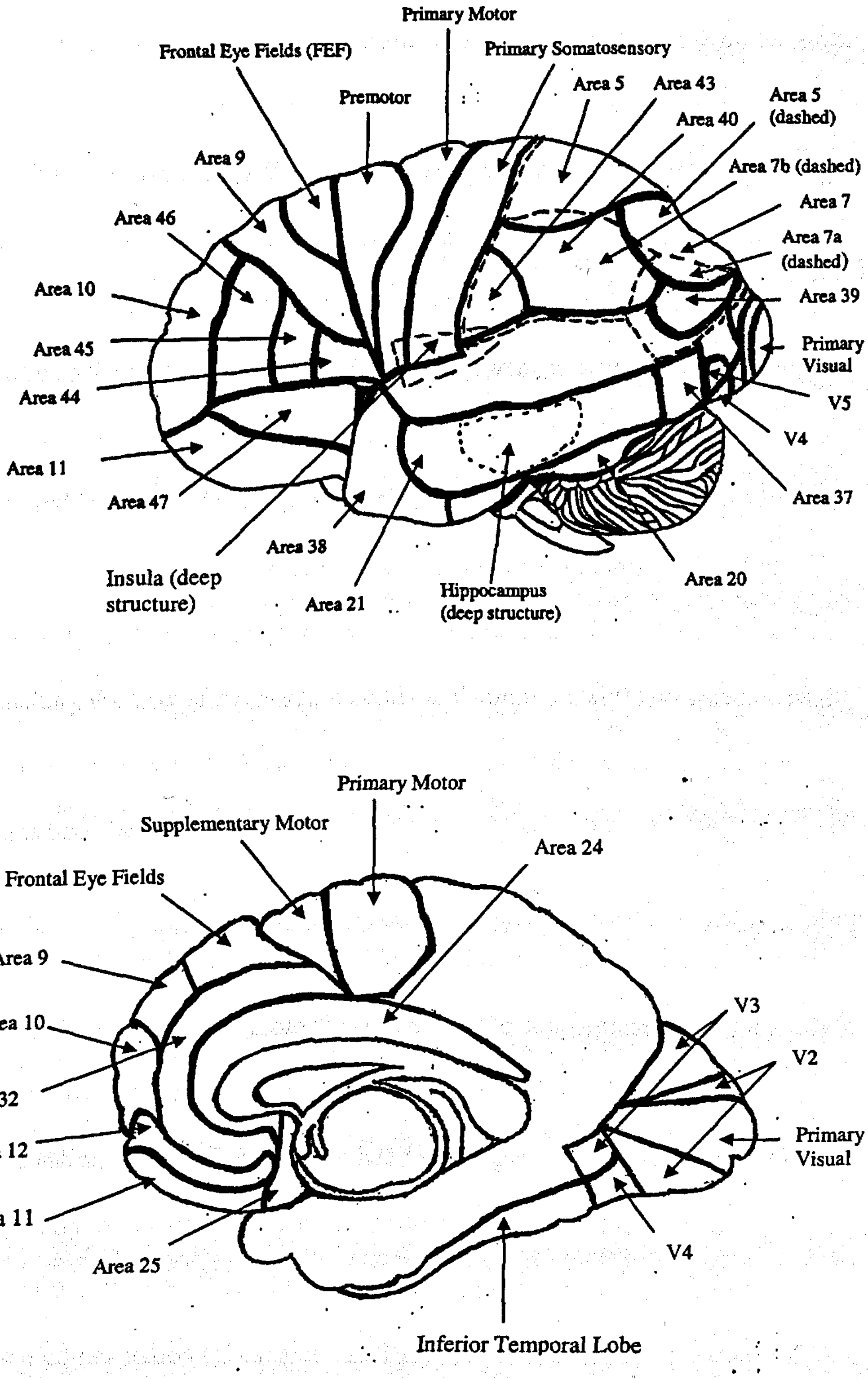

Figure 4. Lateral view in upper panel, medial in lower panel. Positional approximations based on Kolb and Whishaw (1996) and Passingham (1993). Notations based on localisation by Brodmann area, except areas 5, 7a and 7b (dashed) localised by Felleman and van Essen area. Region 7a also contains LIP, VIP and MST mentioned in this thesis. Also presented in Chapter 1 as Figure 2.

prefrontal cortex (D. Milner, personal communication, 2 Oct. 2000). The different connection strengths of the ventral and dorsal streams to the motor areas were used as a basis for designing the current study. A concurrent secondary motor task was used to study differential interference effects on internal visual and external visual imagery. Interference caused by the secondary task would provide evidence that visual imagery, used for mental rehearsal, operates in motor areas. Due to the more direct connection of the dorsal stream to the motor areas, it was predicted that the secondary motor task would affect internal imagery more than external imagery. This prediction assumes that internal visual imagery is egocentrically coded and therefore uses dorsal stream structures while external visual imagery is allocentrically coded in the ventral stream. A finger sequence task (touching thumb to fingers sequentially and continuously) was selected as the concurrent secondary motor task. This task was selected as the cortical activation profile has been largely established.

Finger sequencing activates structures, identified on Figure 4, within the motor cortex including the primary motor area (area 4), the supplementary motor area (medial area 6) and the premotor area (lateral area 6) (Roland, 1993). Primary motor activation is contralateral to the hand performing the sequence, while the supplementary motor area is active bilaterally (Roland, Larsen, Lassen, & Skinhøj, 1980). The premotor area, important to the temporal component of movement co-ordination (Halsband, Ito, Tanji, & Freund, 1993), is associated with the presence of sensory cues, e.g. timing touches to a metronome beat, while the supplementary motor area is active during pure self-generated covert rehearsal (Roland, 1993) and self-initiated movements (those which are not in response to an external prompt) (Passingham, 1993). This profile becomes more complex when long sequences of movements are used, such as the eight-movement sequence that was used in the current study.

Increased sequence length increases activation in the premotor area and cerebellum, illustrating their role in both execution and sequence control (Catalan, Honda, Weeks, Cohen, & Hallet, 1998). Catalan et al. found activation in the posterior portion of the supplementary motor area and primary sensorimotor area (area 3-1-2) was related to sequence execution, regardless of sequence length. Several areas, including the premotor and dorsal visual areas (bilateral posterior parietal and precuneus [dorsocaudal area 7]), were identified as sequence processing areas. Similar results were reported by Sadato, Campbell, Ibáñez, Deiber, & Hallet (1996). Thus, if finger sequencing interferes with mental rehearsal it can be inferred that the imagery activated areas within the motor system, although the specific area(s) activated would remain unspecified.

Experiment 1 (Pilot) Methods

Participants

Twenty-four self-reported right-handed students and staff (ages 19-45) from the University of Wales, Bangor participated. All participants self-reported normal, or corrected to normal, vision. One participant was replaced due to failure to follow instructions. All participants gave their informed consent prior to participating[4].

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[4] The School did not have an ethics committee at the time this research was conducted. The study was designed according to the Ethical Principles of Psychologists and Code of Conduct of the American Psychological Association.

All participants were screened for a minimum of moderate imagery vividness using a slightly modified version (Callow & Hardy, under review) of the Vividness of Movement Imagery Questionnaire (VMIQ) (Issac, Marks, & Russell, 1986). The questionnaire as completed after viewing a videotape illustrating an internal visual perspective and an external visual perspective. The modification, found by Callow and Hardy (under review) to improve the predictive validity, entailed changing the external imagery instructions to "imagine watching yourself" from the original "imagine watching someone else". An additional modification involved instructing participants to perform the imagery with their eyes open. The VMIQ uses a Likert scale ranging from 1 (a clear image) to 5 (no image) to measure the vividness of internal and external visual imagery for 24 different motor tasks. A maximum score of 84 (average score of 3) for both the internal and the external perspectives was taken as a measure of moderate imagery vividness.

Apparatus and Materials

A linear slide rested on a tabletop 30 cm from the edge. Three Light Emitting Diodes (LEDs), 1.8 mm diameter and maximum intensity of 2 mcd, each connected to their own power source, were attached to the side of the slide track (461, 530, and 603.5 mm from the start location, measured to the centre of the diode). The diodes and a digital tape measure were fitted on the side of the track opposite the participant and facing the experimenter. The digital read out of the tape measure was enclosed on three sides, blocking view by the participant, but allowing the experimenter to use a penlight to read the measurements.

A half-silvered mirror used in conjunction with a dark environment prevented visual feedback. The mirror was held by a black metal stand 138 cm x 41 cm x 41 cm (length x width x height) that stood on the table above the linear slide. The top of the stand consisted of a wooden frame holding the mirror (131 cm length x 32 cm width x 0.6 cm thick). The top of the stand was held in place by four bolts; the two bolts closest to the participant were adjusted so that the mirror was angled downward, 70 degrees from horizontal, toward the participant. This adjustment allowed the participants to look forward, rather than straight down, through the mirror.

A videotape was produced in-house to define and illustrate internal and external visual imagery perspectives. The linear slide was set on a table without the stand and a model was asked to move the handle back and forth with the right hand. A camera held above the model's right shoulder, providing a view similar to that of a head mounted camera, was used to illustrate an internal perspective. This "first-person" perspective allowed the arm and hand to be seen while the model moved; no other part of the model's body was visible. The external perspective was recorded with a camera positioned across the room, facing the model and providing a head-to-toe view of the model performing the task. This allowed for a "third-person" point of view. The entire video was shown prior to participants completing the VMIQ screening questionnaire. The video of the relevant perspective was shown before the start of the experiment as a reminder of the type of imagery the participant should perform.

Design

A 2 X 3 (Groups X Condition) design, with repeated factors on Condition, was used. Participants were randomly assigned to either an Internal (Int.) or an External (Ext.) imagery group. Three conditions were counterbalanced. Target position was blocked in order to minimise range effects (Grice, 1968; Poulton, 1973). The Rehearsal (Reh.) condition (target = 461 mm) required that either internal or external visual imagery, depending on Group, be employed as mental rehearsal. The Sequence (Seq.) condition (target = 530 mm) used a finger sequence task, known to activate the motor system, as a concurrent secondary motor task during mental rehearsal. The Mathematics (Math.) condition (target = 603.5 mm) was a control condition that used a mental mathematics suppression task to inhibit mental rehearsal.

Procedure

At the start of the study each participant was informed of which visual imagery perspective to use and was reminded of the nature of the perspective by viewing the relevant part of the videotape. When the study was completed participants were asked for feedback regarding the conditions, a description of their imagery and their ability to adhere to their assigned perspective.

Each trial started with a verbal “READY” signal and the participant’s right hand in the start position. The start position was in line with the participant’s left shoulder and the handle of the slide, and was tactually identified by a piece of velcro 6 cm from the table edge. The experimenter then tapped a button to light the target LED. The depression of the button lasted for approximately 25 milliseconds. Participants were instructed to view the target and then to move the handle to where "the target had been seen", attempting to line up the centre of the handle with the target. Instructions were given that only the right arm and head were allowed to move during a trial. Movement was to be initiated as soon as the target was seen and was to take the form of a single slide – no corrective movements were allowed. It was explained to participants that although movement time was not being measured, the movement should be quick. When participants had stopped moving the experimenter recorded the distance moved. The experimenter returned the handle to the start location. Each participant was given one practice trial, and questions regarding experimental procedures were clarified prior to starting the experiment. Procedures specific to each condition were iterated and clarified prior to each condition. There were 8 movement trials in each condition. No feedback was given during the experiment.

In all three conditions, movements to the target alternated with a second task, with each condition starting and ending with a movement. In the Mathematics condition participants answered mental mathematics problems, e.g. ((11 + 16)/3) or ((7*6)+7). The problems were identical for each participant. In the Rehearsal condition participants performed imagery (Internal visual or External visual) to engage in mental rehearsal of the movement. At the start of the mental rehearsal trials, as in the movement trials, the target LED was lit for approximately 25 milliseconds. Participants were instructed to mentally rehearse sliding the handle to the target as soon as the target was seen. When the target was reached in the participant's mind, the participant said "DONE" and the experimenter proceeded with the next movement trial.

In the Sequence condition participants followed the same procedure as in the Rehearsal condition, with the following exception. Concurrent with mental rehearsal, participants performed a continuous finger sequence task. The sequencing consisted of using the right hand to touch thumb to fingers: index, middle, ring, and little finger in order and then to reverse the order – little finger, ring, middle, index. A single sequence, therefore, required eight movements to complete. Participants began finger sequencing after hearing the "READY" signal. The target LED was then lit for approximately 25 milliseconds and mental rehearsal was initiated as soon as the target was seen. Participants continued to perform the sequence task while performing mental rehearsal and stopped the sequence after saying "DONE" to indicate that the mental rehearsal was finished.

Results

VMIQ Analysis. Two independent samples t-tests were conducted on the VMIQ data to test for differences between groups on their reported vividness of internal and external visual imagery. No difference [$t(22) = 0.931, p > .10$] was found between participants assigned to the Internal imagery group ($M = 51$ ($SD = 19$)) and the External imagery group (45 (11)) on the internal imagery subscale. There was also no difference [$t(22) = 0.622, p > .10$] on the external imagery subscale between the Internal imagery group (62 (15)) and External imagery group (58 (15)).

Principal Analysis. The hypothesis for this study was that the degree of interference caused by the concurrent secondary motor task would be different for

Internal visual and External visual imagery. In the Sequence condition, the use of Internal visual imagery was expected to lead to larger errors than the use of External visual imagery. Means and standard deviations for the linear slide task were calculated for variable error (VE) and absolute constant error (|CE|) (see Table 1).

Table 1. Means and (Standard Deviations) in Rehearsal [Reh.], Sequence [Seq.] and Mathematics [Math.].

	Absolute Constant Error (mm)			Variable Error (mm)		
	Reh.	Seq.	Math.	Reh.	Seq.	Math.
Int	34.5 (24.6)	42.5 (31.6)	46.4 (27.7)	15.2 (4.8)	18.4 (7.8)	23.8 (9.4)
Ext	31.7 (19.3)	41.9 (31.8)	41.2 (31.5)	17.2 (4.1)	21.4 (7.1)	20.8 (12.0)

Variable error and absolute constant error were analysed using 2 X 3 (Groups X Conditions) ANOVA's, with repeated measures on the second factor. As recommended by Schutz and Gesseroli (1993), all violations to sphericity were Huynh-Feldt corrected except those with epsilon < .75 which were Greenhouse-Geisser corrected.

For VE, there was a main effect for Condition, $F(2,44) = 4.371$, Huynh-Feldt adjusted, $p = .02$, $\eta^2 = .166$, but no interaction [$F(2,44) = 1.232, p > .10$] or effect for Group [$F(1,22) = 0.089, p > .10$]. Follow up analysis on the effect for Condition using Tukey's Honestly Significant Difference test found that errors in the Rehearsal condition ($M = 16.2$ mm) were significantly smaller than those in the Mathematics condition (22.3), $p < .05$. Analysis of |CE| failed to reach significance ($p > .10$): Condition $F(2,44) = 2.066$, Group $F(1,22) = 0.092$, and Condition x Group $F(2,44) = 0.079$.

Discussion

The results indicated that using mental rehearsal led to smaller variable errors than did the answering of mathematics questions, suggesting that the suppression task was effective. There were no effects of finger sequencing or between group differences. The highly exploratory nature of the research meant that there could be methodological issues that had not been previously identified. A review of the feedback provided by participants identified three themes important to consider before any attempt to replicate the study could be made. First, participants in both groups found the Sequence condition to be very difficult compared to the Rehearsal condition. This was taken as reassurance that some form of interference was in fact occurring. It was, however, problematic that compliance with the instructions to continually tap fingers relied on self-reports. Second, four people in the External imagery group reported that they had difficulty adhering to the external perspective and would have preferred to use internal visual imagery. It could have been that the nature of the task, as understood by the participants, encouraged internal visual imagery more than external visual imagery. Participants in the current study had been asked to image the whole of the movement, but if they had focused only on the end (target acquisition) and not the form of the movement, then external imagery might have been less useful. It has previously been noted that external visual imagery is significantly more effective than internal visual imagery when people are learning the form of a gross body movement (Hardy & Callow, 1999). Third, six people (4 Int., 2 Ext.) stated that some degree of kinaesthetic imagery accompanied their visual imagery. One participant specified that the kinaesthetic imagery only occurred in the Rehearsal condition.

The possibility that there was a learning curve for the movement task was also explored. One participant from the study was asked to return for a second session. The same apparatus was used. Three new targets (220 mm, 656.5, and 383) were attached to the linear slide. The participant then performed 28 movement trials to each target, starting with a block of 28 to the 220 mm target, then the 656.5 mm target, and finally the 383 mm target. Verbal knowledge of results was given on each trial: "on" meaning that movement had placed the handle directly in line with the LED target, "undershoot close", "overshoot close", "undershoot far", "overshoot far". Twelve more trials (four in a block, target order remained the same) were administered. In total 96 trials were performed in one hour. Additional trials were not used, as the participant was tiring of the task, an effect that was possibly compounded by the darkness of the room. The raw data was graphed and inspected for learning curves and plateaus. None were found. However, the first two trials of the second and third block looked like familiarisation trials.

Prior to conducting Experiment 2, several methodological changes were made. A maximum difference of 24 points between each person's subscales on the VMIQ was added as a screening requirement making it more likely that participants could use either perspective equally well. The imagery instructions were made more explicit with specific instructions given to focus on the whole form of the movement, not just the endpoint. Adherence to sequencing was assessed using a computer keyboard and a repetitive eight key sequence using all four fingers of the right hand. A post-experimental manipulation check questionnaire was used to gather systematic feedback from participants (i.e., adherence to their assigned perspective, the extent to which kinaesthetic imagery was or was not used and in which condition(s), if a different perspective was desired, and to elicit descriptions of each participant's imagery). Additional warm up trials were added. Additional trials were administered during the experiment so that the first three of each block could be removed from analysis, which was deemed important to the elimination of familiarisation effects for the sequencing task on the keyboard.

Experiment 2 Methods

Participants

Twenty-four self-reported right handed students (ages 18-35) from the University of Wales, Bangor participated in this study. All participants had normal, or corrected to normal vision. Seven participants were replaced: one for not following experimental procedures and six for an inability to adhere to their assigned imagery perspective. Ethical approval for this study was obtained from the Ethics Committee of the School of Sport, Health and Exercise Sciences.

All participants were screened using the VMIQ as described in Experiment 1. A maximum score each of 84 for internal and external perspectives was taken as a measure of moderate imagery vividness, as in Experiment 1. An additional requirement in Experiment 2 of a maximum difference of 24 points between the two perspectives was employed to insure all participants could use either perspective equally well.

Apparatus and Materials

Finger sequencing compliance was monitored via a keyboard attached to an IBM compatible 486 PC. The keys to be used (F, G, H, J, and spacebar) were fitted with medium fine sandpaper to allow participants to tactually locate the keys in a dark room. A software program written in-house recorded key strikes. All other materials remained as they were in Experiment 1.

Design

The design remained a 2 X 3 (Groups X Condition) design, with repeated factors on Condition. Presentation of conditions was counterbalanced. Target position was blocked to minimise range effects (Grice, 1968; Poulton, 1973): Mathematics (target = 461 mm), Rehearsal (target = 530 mm), and Sequence (target = 603.5 mm).

Procedure

The general procedures were identical to the first study with two exceptions. Instructions to image the form of the movement (reaching for the handle and sliding it along the track) were stressed to a greater extent then in Experiment 1. Participants were instructed to start mentally rehearsing sliding the handle to the target as soon as the target was seen, focusing on the whole movement – to look for the light, imagine reaching out and taking hold of the handle, and sliding it until it was lined up with the target. In addition, instructions were given to line up the centre of the handle to the target (not to the visual angle of the target, which was greater with the further targets), correcting an oversight which one participant had commented on in the post experimental interview of Experiment 1. All other general instructions remained as they had been in Experiment 1. Each participant was given three practice trials, one to each target with verbal knowledge of results provided ("on target", "overshot", "undershot"), and the general procedures were clarified prior to starting the experiment. Procedures specific to each condition were iterated and clarified prior to each condition, as in Experiment 1. There were 15 movement trials in each condition, the first 14 of which were followed by a task (mathematics questions, mental rehearsal, or mental rehearsal while finger sequencing). No feedback was given during the experiment. When finished, participants were administered a post-experimental manipulation check questionnaire (see Appendix A).

The Mathematics and Rehearsal conditions were identical to those in the first experiment. The Sequence condition differed in that the finger sequence task was performed on a computer keyboard, located on a table to the right of the participant. Participants began the finger sequence task by pressing the spacebar on the keyboard with their thumb after hearing the "READY" signal. Finger sequencing consisted of using the right hand to continuously type a sequence on the keyboard ("F, G, H, J") using the index, middle, ring, and little finger and then to reverse ("J, H, G, F") the sequence – little, ring, middle, index finger. The target was then seen and mental rehearsal was initiated. Participants continued to perform the sequencing task while performing mental rehearsal and stopped the sequencing, by again pressing the spacebar, after they had said "DONE" to indicate that the mental rehearsal was finished. The experimenter monitored sequencing compliance on a dimly lit monitor turned away from the participant. Any pauses in the sequencing led to verbal prompting that the sequencing should continue.

Results

VMIQ Analysis. Two independent sample t-tests were conducted on the VMIQ data to assess the differences between the Internal and External imagery groups on the questionnaire subscales. On the subscale of internal visual imagery, the Internal imagery group ($M = 44$ (SD = 14)) did not differ from the External imagery group (47 (15)), $t(22) = 0.461$, p > .10. There was also no between groups difference on the external imagery subscale, $t(22) = 0.869$, $p > .10$; the Internal imagery group mean score of (54 (16)) did not differ from the External imagery group (49 (11)).

Initial Analysis. It was hypothesised that the degree of interference caused by the concurrent secondary motor task would be different for Internal visual and External visual imagery. In the Sequence condition, the use of Internal visual imagery was expected to lead to larger errors than the use of External visual imagery. Interference was measured using variable error (VE) and absolute constant error (|CE|).

The data was visually inspected and the first three trials were removed from each condition to minimise familiarisation effects. Outliers and extreme values, identified using box-and-whisker plots (Tukey, 1977), were removed from each participant's raw data set. A total of 11 data points were removed from Mathematics, 10 from Sequence, and nine from Rehearsal. Ten participants had no outliers. Means and standard deviations were then calculated (see Table 2). Initial analysis employing 2 x 3 (Group x Condition) ANOVA's, with repeated measures on the second factor, for absolute constant error and variable error showed no significant effects ($p > .10$): variable error analysis of Condition $F(2,44) = 1.985$, Group $F(1,22) = 0.028$ and Condition X Group $F(2,44) = 0.085$, and absolute constant error analysis of Condition $F(2,44) = 0.423$, Group $F(1,22) = 0.582$ and Condition x Group $F(2,44) = 0.345$. The data were re-inspected, with cross-referencing to the post experimental manipulation checks.

Table 2. Means and (Standard Deviations) in Rehearsal [Reh.], Sequence [Seq.] and Mathematics [Math.].

	Absolute Constant Error (mm)			Variable Error (mm)		
	Reh.	Seq.	Math.	Reh.	Seq.	Math.
Int	21.9 (12.5)	24.3 (19.9)	23.9 (16.4)	17.7 (3.9)	20.1 (6.8)	16.8 (6.2)
Ext	29.1 (19.7)	31.3 (27.1)	23.7 (20.5)	19.1 (7.8)	18.5 (7.9)	16.4 (6.0)

Manipulation Check. All participants in the External imagery group reported using imagery of themselves in motion, rather than imagery of someone else. In addition, most participants reported using kinaesthetic imagery in conjunction with visual imagery in either the Rehearsal or Sequence condition, or both. It was reasoned that kinaesthetic imagery could have confounded the visual imagery results as kinaesthetic imagery uses some of the same neural structures as finger sequencing (e.g., Pfurtscheller & Neuper, 1997; Catalan et al., 1998). Inspection of the data suggested that absolute constant error (|CE|) was affected by the use of kinaesthetic imagery; the |CE| data was divided into "used" and "did not use" kinaesthetic imagery. Participants who reported "not sure" about the use of kinaesthetic imagery were not re-analysed. The manipulation check had not asked specifically about the use of kinaesthetic imagery in the Mathematics condition and therefore only the Rehearsal and Sequence conditions were re-analysed. The data was collapsed over imagery groups due to limited numbers.

Secondary Analysis. An unweighted means analysis compared the difference in |CE| between those who used and did not use kinaesthetic imagery in the Rehearsal condition to the difference between those who used and did not use kinaesthetic imagery in the Sequence condition. The analysis confirmed that kinaesthetic imagery affected the two conditions differently, $F(1,33) = 11.349, p < .01$ (see Figure 5). Three subsequent t-tests were conducted. An independent sample t-test was applied to the Rehearsal condition data to compare those who used kinaesthetic with visual imagery to those who did not: a two-tailed test was used as there was no strong theoretical argument to assume kinaesthetic imagery would be detrimental or beneficial to the task[5]. A second independent sample t-test compared the performance of participants who used and did not use kinaesthetic imagery with visual imagery in the Sequence condition. A one-tailed test was used as both kinaesthetic imagery and finger sequencing affect the motor and sensorimotor cortices (Roland et al., 1980; Porro, Cettolo, Francescato, &

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[5] There are no reports in the literature of kinaesthetic imagery hindering performance. In addition, kinaesthetic imagery seems to benefit performance only when the performer has expertise in the task (Hardy & Callow, 1999).

Baraldi, 2000; Catalan et al., 1998; Pfurtscheller & Neuper, 1997) and therefore might interfere with one another. Independent samples were used for the first two t-tests as the Rehearsal and Sequence data was neither completely dependent, or independent. A paired sample t-test was then conducted on the data of the participants who did not use kinaesthetic imagery in either the Rehearsal or Sequence condition to determine if finger sequencing led to larger errors. A two-tailed test was used as the analysis contained both internal and external imagers.

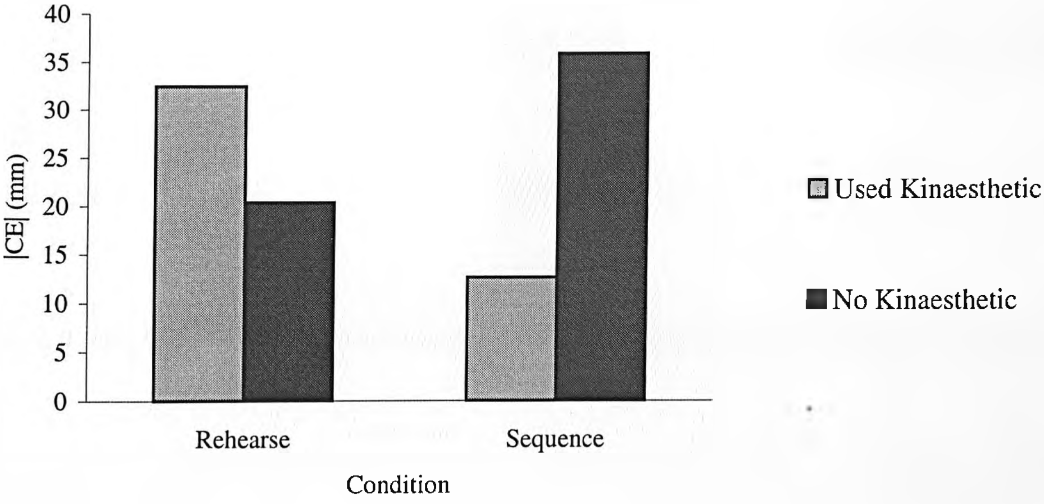

Figure 5. Effect of Kinaesthetic Imagery.

The use of kinaesthetic with visual imagery in the Rehearsal condition appeared to produce greater absolute constant errors than using visual imagery alone (see Figure 5). Nine participants (5 Int., 4 Ext.) reported kinaesthetic imagery (*M*=32.4 mm (*SD*=22.1)) while 11 (3 Int., 8 Ext.) reported no kinaesthetic imagery (20.4 (13.4)). A two-tailed t-test found no difference in performance, $t(18) = 1.503, p = .15$.

In the Sequence condition, using kinaesthetic imagery in addition to visual imagery appeared to cause smaller absolute constant errors than visual imagery alone (see Figure 5). Five participants (2 Int., 3 Ext.) used kinaesthetic imagery (*M*=12.7 mm (*SD*=19.8)) while 12 (5 Int., 7 Ext.) did not (35.8 (26.2)). The one-tailed t-test was significant, $t(15) = 1.763$, $p = .05$, suggesting interference (a "cancelling" effect) between the kinaesthetic imagery and finger sequencing.

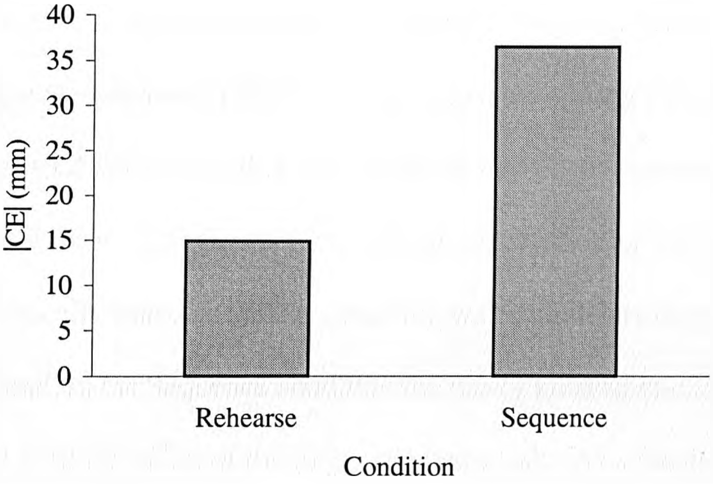

Figure 6. Visual Imagery Only.

Eight participants (2 Int., 6 Ext.), a sub-sample of the "did not use" data from the first two t-tests, reported not using kinaesthetic imagery in either the Rehearsal or Sequence condition. A significant difference between conditions was found, $t(7) = 2.734$, $p = .03$, two-tailed. Mean performance (see Figure 6) in Rehearsal (*M*=14.9 mm (*SD*=9.9)) was better than in Sequence (36.4 (28.9)).

Discussion

The initial analysis found no support for the original hypotheses of the study. There were no effects of finger sequencing, suppression caused by the mathematics, or between group differences. Subsequent consideration of the post-experimental manipulation check indicated a possible confound by kinaesthetic imagery. Kinaesthetic imagery was used by participants in both the internal and external imagery group (cf., Hardy & Callow, 1999; White & Hardy, 1995).

Taken together, the secondary analyses provide some evidence that visual imagery of movement operates in parts of the brain also involved in finger sequencing. First, the larger observed errors by people using only visual imagery in the Sequence condition (*M*=35.8 mm) versus those using only visual imagery in the Rehearsal condition (20.4 mm) suggests that finger sequencing caused interference. This first point is only an observation of the data; it could not be statistically tested as neither condition was completely dependent, or independent. Second, in the Sequence condition the use of kinaesthetic imagery appears to have cancelled the effect of the finger sequence task. As a result, the t-test for the Sequence condition could be thought of a test of visual imagery only versus visual imagery plus finger sequencing; errors by those people using visual imagery alone were significantly smaller. Third, the paired sample t-test conducted on the data of the people who did not use kinaesthetic imagery in either the Rehearsal or the Sequence condition found that the errors in the Rehearsal condition were significantly smaller than those in the Sequence condition. Which brain areas are possibly shared, however, remains unclear.

It is unlikely that the primary sensorimotor area (area 3[a and b]-1-2), which is involved in both finger sequencing (e.g., Catalan et al., 1998) and kinaesthetic imagery (e.g., Pfurtscheller & Neuper, 1997), is involved in visual imagery. The primary sensorimotor (kinaesthesis, touch, and pressure) area is part of the somatosensory system (Kolb & Whishaw, 1996). The primary sensorimotor area sends outputs to secondary somatosensory areas (including areas 5 and 7) and the primary motor cortex (see Figure 4 for location of structures). Position and muscle movement are primarily represented in area 3a; area 2 represents deep pressure and joint sense (Kolb & Whishaw, 1996). Thus, no visual information is processed within the primary sensorimotor area.

Kinaesthetic imagery has also been shown to activate the primary motor area: imagined continuous movement of a cube between the thumb and fingers of one hand (Schnitzler, Salenius, Salmelin, Jousmäki, & Hari, 1997), imagined finger sequencing (Porro, Francescato, Cettolo, Diamond, Baraldi, Zuiani, Bazzocci, & di Prampero, 1996; Porro, Cettolo, Francescato, & Baraldi, 2000), and imagining forming a fist (Lotze, Montoya, Erb, Hülsmann, Flor, Klose, Birbaumer, & Grodd, 1999). Lotze et al. also found that the supplementary motor area and premotor area were equally active during real and imagined fist forming (see also Porro et al., 1996; 2000). The effect of kinaesthetic imagery on motor and sensorimotor areas may explain the cancellation effect that appeared in the Sequence condition. This explanation is however purely speculative. In addition, the explanation is problematic as the finger sequence task did not affect visual imagery alone in the same manner as it affected the combined use of visual and kinaesthetic imagery. This suggests that there is a resource that visual imagery may use to affect the motor system that is not used by either finger sequencing or kinaesthetic imagery, for which no theoretical explanation is available.

An additional, or alternative, explanation involves conflicting neuromuscular signals in the periphery. Recall that in the Sequence condition, participants who used kinaesthetic plus visual imagery while finger sequencing had significantly smaller errors than those people who used visual imagery alone. Arguably, kinaesthetic imagery is more closely related to actual motor performance as it can involve the sensation of muscle tension and pressure (cf., Hall & Martin, 1997). Jacobson (1932) differentiated between visualisation of a task and imagining the muscular sensation that would accompany the task. He measured voltage changes in the ocular region and the muscles of the right arm during imagined flexing of the right arm. Changes in the ocular region occurred during visualisation, while changes in the muscles occurred during kinaesthetic imagery. The innervation described by Jacobson "may be capable of providing kinaesthetic feedback (Corbin, 1972, p. 102)", or possibly "primes the motor pathways with decending volleys (Jeannerod, 1994, p. 191)". Thus, it is possible that finger sequencing and kinaesthetic imagery were both sending and/ or receiving conflicting signals to/ from the periphery.

Summary and Conclusions

The underlying notion of these studies was that external and internal visual imagery might affect the motor cortex via structures in the ventral and dorsal visual streams, respectively. The dorsal stream has relatively direct connections from the posterior parietal lobe to the motor cortex (Passingham, 1993). The egocentric nature of the coding in the dorsal stream (Milner & Goodale, 1995) suggests that if a form of visual imagery activates structures there, it should be internal visual imagery. The ventral stream is believed to supply the dorsal stream with information regarding the external environment whenever the dorsal stream is forced off-line, as in delayed reaching tasks (Milner & Goodale, 1995). In doing so the ventral stream also affects the motor system. The allocentric coding of the external environment characterising the ventral stream (cf., Milner & Goodale, 1995) seems similar to the coding employed in external visual imagery.

The secondary analyses of Experiment 2 suggest that the finger sequence task interfered with visual imagery of movement. This provided some evidence that visual imagery of movement involves structures in the motor cortex. The strength of the connection between the motor cortex and internal, or external, visual imagery could not be distinguished, possibly due to a confound of kinaesthetic imagery. In light of the original hypothesis it should be specified that six of the eight people who did not use kinaesthetic imagery (those analysed with the paired sample t-test) were in the External imagery group. All participants in the External imagery group reported imagery of the self in motion, rather than imagery of someone else. Research with patients has indicated that internal visual imagery involves the inferior parietal lobe, while external (of someone else) visual imagery activates inferior temporal visual areas (Sirigu & Duhamel, 2001). External (of self) visual (Deiber et al., 1998) imagery activates supplementary motor and premotor areas in addition to the inferior parietal lobe. Thus, the significantly smaller errors in the Rehearsal condition, compared to the Sequence condition, for those people who did not use kinaesthetic imagery may be explained by involvement of motor areas during external visual imagery.

CHAPTER 3

COLOUR AND MOTION STIMULI FACILITATION OF VISUAL IMAGERY OF MOVEMENT[6]

Abstract

This study aimed to activate colour area V4 in the ventral pathway and motion area V5 in the dorsal pathway to investigate interference effects with visual imagery of movement, as the cortical areas underlying such imagery remain unclear. Participants (*N*=18) were assigned to either internal visual or external visual imagery. Actual movements involved sliding a handle along a trackway to one of 3 possible light emitting diode targets, 461, 530, and 604 mm distant from the start position. Three blocked conditions were used, with rehearsal and actual movements alternating within each condition: mental rehearsal while viewing a solid colour filling a computer screen (Col.), mental rehearsal while viewing a moving dot (5°/sec) on a computer screen (Mot.), mental rehearsal with the screen turned off but eyes open (Reh.). Conditions and targets were counterbalanced. Absolute constant error analysis found that error magnitude was significantly smaller in Col. than in Reh. Error variability was significantly smaller for external imagery in both Col. and Mot., compared to Reh. These results indicate the opposite of interference effects. Several explanations of facilitation were considered and rejected. It was inferred that the bright colours (Col.) particularly, and the black dot on white (Mot.), enhanced the internal representations allowing people to more vividly imagine themselves performing. Increased vividness

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[6] An abstract for this research is published in the conference proceedings of the First Joint Meeting of the European Brain and Behaviour Society and the European Behavioural Pharmacology Society in 2001 (A. Fourkas, L. Hardy, & M. Khan (2001) *Behavioural Pharmacology, 12,* supplement 1, S36), and a full paper is currently being prepared for submission.

apparently aided spatial coding in external imagery more than internal imagery, suggesting that participants considered the task to be form based.

Introduction

Internal visual and external visual imagery of movement can affect the human motor system (e.g., Budney, Murphy, & Woolfolk, 1994; White & Hardy, 1995; Hardy & Callow, 1999). Internal visual imagery seems to use an egocentric coding system (cf., Sirigu & Duhamel, 2001). The use of egocentric codes (cf., Milner & Goodale, 1995) is suggested in that during internal visual imagery the person is within his own image, and the body-centred spatial mapping of the image changes as the person imagines moving through or interacting with the environment. This definition of internal imagery is in contrast to that which describes internal imagery as predominately kinaesthetic in nature (e.g., Hale, 1981; Jeannerod, 1995). External visual imagery may be allocentric in nature. Allocentric coding involves the use of points in the environment to triangulate spatial relations between objects without regard to the physical location of the observer (Dijkerman, Milner, & Carey, 1998). In an external visual image, the person can not only "watch" himself interact with the environment but also can be conceptualised as one of the objects in the image. The area where the imaged action takes place is "over there". The person can view himself from any angle; allocentric coding allows a person to recognise an object from any angle (Milner & Goodale, 1995). From the lack of body-centred co-ordinates, and the ability to view from any angle, in allocentric coding and external imagery, it is inferred that the two are related.

Egocentric and allocentric coding occur in the dorsal and ventral visual streams, respectively (Milner & Goodale, 1995). The dorsal visual stream carries information from the primary visual area in the occipital lobe to visual areas in the parietal lobe (see Figure 7). Information carried from the primary visual area to the visual areas of the temporal lobe travels through the ventral visual stream. According to Milner and Goodale, the dorsal stream uses egocentric coding to guide on-line (concurrent) motor responses to the environment, while the ventral stream uses allocentric coding for perception and recognition, or to temporarily store information about spatial relations in the environment. When on-line motor responses are not possible, as when responses are delayed or the visual information suddenly disappears, it is believed that the ventral stream feeds spatial information from storage into the dorsal stream to guide action (Milner & Goodale, 1995).

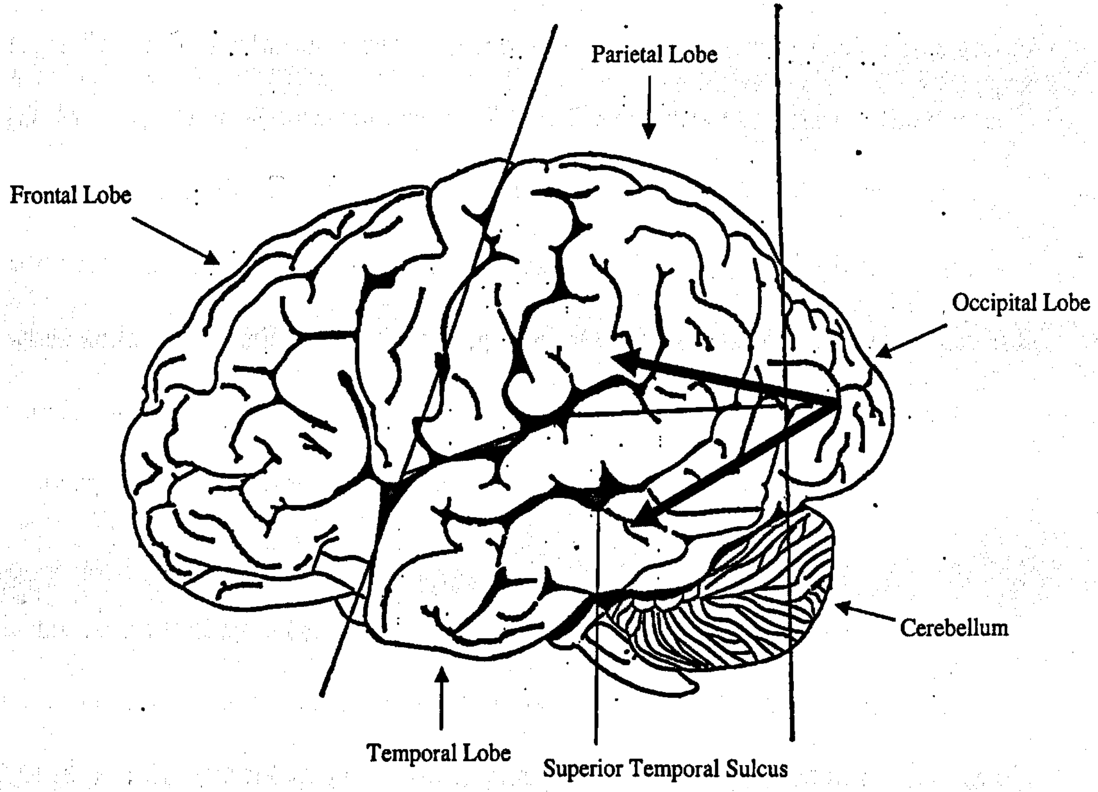

Figure 7. Illustration with location of lobes, cerebellum, and superior temporal sulcus (possible part of the third visual pathway). Large arrow from the occipital lobe to visual areas of the parietal lobe represent the dorsal visual stream. Large arrow from the occipital lobe to visual areas of the temporal lobe represent the ventral visual stream. This figure is also presented in Chapter 1 as Figure 1, and Chapter 2 as Figure 3.

There have been reports that visual imagery and visual perception share neural structures (e.g., Farah, Péronnet, Gonon, & Giard, 1988). However, visuospatial imagery tasks (e.g., mental rotation, mental map scanning) differ from visual imagery of movement in both substance and intention. Several aspects of Milner and Goodale's (1995) theory are extremely useful when speculating on the neural structures involved in visual imagery of movement. The concepts of egocentric and allocentric coding are viable descriptions of internal and external visual imagery perspectives. In addition Milner and Goodale have suggested that from moment to moment egocentric information changes, and therefore the dorsal stream relies on stored algorithms or "knowledge" of the normal relations between physical properties. Thus, even though there is no evidence that imagery, regardless of it's relation to motor behaviour, can be considered as on-line action (D. Milner, personal communication, 2 Oct. 2000), structures within the dorsal stream contain information that would be useful during internal visual imagery. With regards to the ventral stream, the function of storing spatial information when action is inhibited, and then supplying it to the dorsal stream when action is possible again, would be a useful mechanism through which external visual imagery could affect the motor system.

In the current study, a behavioural approach was taken to investigate whether certain neural structures are involved in visual imagery of movement. Visual imagery of movement was used for mental rehearsal (as opposed to other uses of visual imagery of movement, e.g., manipulating motivation or anxiety). It was hypothesized that mental rehearsal performed without a concurrent task would lead to superior performance (smaller errors) than would visual imagery of movement with a concurrent task, provided the concurrent task and visual imagery use the same structures. The concurrent task of attending to visual stimuli was selected. A slow motion stimulus was used to produce activation in area V5 within the dorsal stream (ffytche, Guy, & Zeki, 1995; 1996), and colour stimuli were used to activate V4 in the ventral stream (Zeki & Marini, 1998) (see Figure 8 for location of structures).

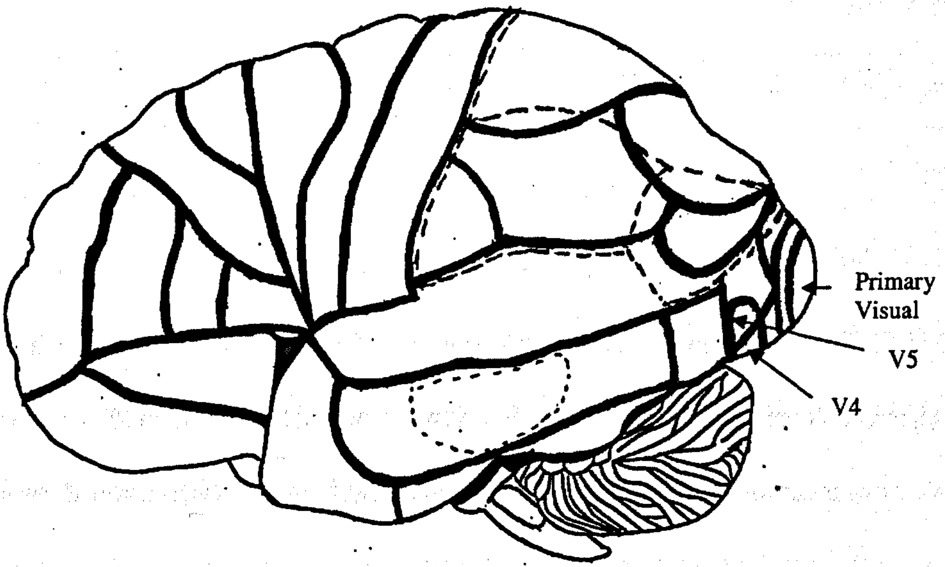

Figure 8. Lateral view of locations of areas V4 and V5 in the occipital lobe. Positional approximations based on Kolb and Whishaw (1996).

Area V5 is known to respond to motion stimuli (e.g., Chawla, Phillips, Buechel, Edwards, & Friston, 1998). Slow motion stimuli activate the cortical pathway (dorsal stream) from the primary visual cortex to V5 (ffytche, Guy, & Zeki, 1995). In an attempt to activate the pathway from the primary visual cortex to area V5 (cf., ffytche, Guy, & Zeki, 1995; 1996), participants were asked to visually track a slow moving black dot on a white background while performing mental rehearsal. Although mental rehearsal using either an internal visual or external visual image involves imagined motion, it was predicted that the motion stimulus would disrupt internal visual imagery more than external visual imagery. This prediction was based on the presumed use of egocentric coding during internal visual imagery and that internal visual imagery is therefore manipulated within the dorsal stream.

The colour processing system extends through the ventral steam from the primary visual area to area V4 (Zeki & Marini, 1998). Area V4 provides colour constancy, the unchanging perception of colour regardless of the spectral composition of the available light reflecting off surfaces (Zeki & Marini, 1998; Bartels & Zeki, 2000). Anecdotal reports of images being coloured during mental rehearsal are not uncommon (e.g., the colour of a tennis ball, uniforms, features in the environment). It is unclear, however, whether the perception of colour and the imagination of colour share neural structures (cf., Farah, Hammond, Levine, & Calvanio, 1988) or not (cf., Howard, ffytche, Barnes, McKeefry, Ha, Woodruff, Bullmore, Simmons, Williams, David, & Brammer, 1998). In an attempt to activate area V4, participants in the present study viewed a pseudo-randomly selected colour while performing mental rehearsal. External visual imagery was expected to be more affected by the presence of colour stimuli than would internal visual imagery. This prediction assumes that external visual imagery uses allocentric coding and that allocentric coding occurs in the ventral visual stream where area V4 is located.

Methods

Participants

Eighteen self-reported right-handed students (ages 18 - 40) from the University of Wales, Bangor participated in this study. All participants self-reported normal, or corrected to normal, vision. Four participants were replaced due to failure to adhere to the experimental procedures. Approval for this study was obtained from the Ethics Committee of the School of Sport, Health and Exercise Sciences at the University of Wales, Bangor.

All participants were screened for a minimum of moderate imagery vividness using a slightly modified version (Callow & Hardy, under review) of the Vividness of Movement Imagery Questionnaire (VMIQ) (Issac, Marks & Russell, 1986). The questionnaire was completed after viewing a videotape (video 1, described below) illustrating an internal visual perspective and an external visual perspective. The modification, found by Callow and Hardy (under review) to improve predictive validity, entailed changing the external imagery instructions to "imagine watching yourself", rather than the original "imagine watching someone else". An additional modification involved instructing participants to perform the imagery with their eyes open. The VMIQ uses a Likert scale ranging from 1 (a clear image) to 5 (no image) to measure the vividness of internal and external visual imagery for 24 different motor tasks. A maximum score of 84 on each subscale (internal visual and external visual imagery perspective) was taken as a measure of moderate imagery vividness. A maximum spread of 24 points between an individual's score on the two subscales was used to ensure all participants could use either perspective equally well.

Materials and Apparatus

The linear slide rested on a tabletop 30 cm from the edge. Three Light Emitting Diodes (LEDs), 1.8 mm diameter and maximum intensity of 2 mcd, each connected to their own power source, were attached to the side of the slide (461, 530, and 603.5 mm from the start location, measured to the centre of the diode). The diodes and a digital tape measure were fitted on the side of the slide opposite the participant and facing the experimenter. The digital read out of the tape measure was enclosed on three sides, blocking view by the participant but allowing the experimenter to use a pen light to read the measurements.

A half-silvered mirror used in conjunction with a dark environment prevented visual feedback. The mirror was held by a black metal stand 138 x 41 x 41 cm (length x width x height), which stood on the table above the linear slide. The top of the stand consisted of a wooden frame holding the mirror (131 cm length x 32 cm width x 0.6 cm depth). The wooden frame was held in place by 4 bolts; the two bolts closest to the participant were adjusted so that the mirror angled downward, 70 degrees from horizontal, toward the participant. This adjustment allowed the participant to look forward, rather than straight down, through the mirror.

Two interference stimuli (colour and slow motion), written in Java, were run on a Dell 420 computer connected to a 19 inch Dell branded Trinitron monitor, with a 14 inch horizontal screen (refresh rate = 85 Hz). The monitor was located to the left of the participant's body (distance = 1 meter).

A videotape was produced in-house (herein labelled "video 1") to define and illustrate internal and external visual imagery perspectives. The linear slide was set on a table without the stand and a model was asked to move the handle back and forth with the right hand. A camera held above the model's right shoulder, providing a view similar to that of a head mounted camera, was used to illustrate an internal perspective. This angle allowed the arm and hand to be seen; no other part of the model's body was visible. The external perspective was recorded from across the room while facing the model. The entire video was shown prior to completion of the screening questionnaire and the relevant perspective was shown just before the start of the experiment, as a reminder of the type of imagery the participant should perform.

In a second videotape (herein labelled "video 2"), a model moved the handle along the slide to the targets (a block of five movements to each target), precisely as would be done by participants in the study. The lights were left on for the video (the room was dark in the actual experiment) to aid the participants in forming clear images. Two versions, one from an internal visual perspective and one from an external visual perspective, were recorded.

Design

A 2 x 3 (Groups x Condition) design, with repeated factors on Condition, was used. Participants were randomly assigned to either the Internal perspective (Int.) or External perspective (Ext.) group. The conditions (Rehearsal, Colour, and Motion) were randomly ordered. Condition and target were counterbalanced[7].

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[7] Although target presentation was blocked in order to minimize range effects in Chapter 2, it was determined that the design could confound error as there is some evidence that variable error increases with distance (e.g., Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979).

Procedure

Participants were reminded of the visual perspective to which they had been assigned by viewing the relevant perspective on video 1. In addition, they were instructed not to use kinaesthetic imagery. To aid participants in only employing a visual image, video 2 was played prior to each condition and displayed movement to the condition specific target, viewed from the relevant perspective. It was reasoned that a video showing a model moving to specific targets would provide participants with a clearer impression of what exactly to image, therefore decreasing any need to "fill in the gaps" using kinaesthetic imagery. When the participants had finished the study, they completed a manipulation check questionnaire regarding imagery content and the ability to follow instructions (see Appendix B).

Each trial started with a verbal "READY" signal and with the participant's right hand in the start position. The start position was in line with the participant's left shoulder and the handle of the slide, tactually identified by a piece of velcro 6 cm from the table edge. Participants were instructed to view the target. The experimenter tapped a button momentarily lighting the target LED (approximately 25 milliseconds). The participant then attempted to line up the centre of the handle to the target. Participants were instructed that only their head and right arm were allowed to move. Movement was to be initiated as soon as the target was seen and was to take the form of a single slide – no corrective movements were allowed. It was explained to participants that although movement time was not being measures, the movement should be quick. When participants stopped moving, the experimenter recorded the distance moved. The experimenter returned the handle to the start. Each participant received one practice trial to each of the three targets, with verbal knowledge of results provided ("on target", "close under-/over-shoot", "far under-/over-shoot"). All general procedures were clarified prior to starting the study, and condition specific procedures were iterated prior to the relevant condition. There were 15 actual movement trials, alternating with 14 imagery trials, in each condition starting and ending with an actual movement trial. No feedback was provided during the experiment.

Before initiating mental rehearsal, participants were required to turn their head and torso leftward, and to look at the computer monitor. At the end of each mentally rehearsed trial, participants turned towards the right and resumed the correct body position for performing the linear slide task. Throughout the Rehearsal (Reh.) condition the monitor was dark. Participants started mentally rehearsing, with eyes open, facing an un-illuminated computer monitor as soon as a verbal "START" signal was given. The imagery instructions to focus on the "seeing" the whole movement – imaging reaching out and taking hold of the handle, sliding it to line up with the target – were reinforced via the videotape of the model doing the task (video 2). When the target was reached in the participant's mind, the participant said "DONE" and the experimenter proceeded with the next movement trial.

The Colour (Col.) and Motion (Mot.) conditions were identical to the Rehearsal condition with the following exception. Prior to initiating mental rehearsal, participants turned their head and torso to the left and fixated their eyes on the computer monitor. As the participant turned, the experimenter pressed the right mouse key of a computer and a condition specific stimulus (a colour or a slowly moving dot) appeared on the monitor. Both the colour and slow motion stimuli started with a black screen. In the Colour condition, the mouse click caused a psuedo-randomly selected colour to fill the screen. In the Motion condition, the mouse click caused a black dot, diameter 1 inch, to begin moving from left to right across a white background at the rate of 5 degrees per second, when viewed from a distance of 1 meter (39.37 inches). Participants were instructed to do their visual imagery while attending to the stimulus on the computer monitor. When the imagery was complete and the participant said "DONE", the experimenter again tapped the right mouse key removing the stimulus and causing the monitor to go dark. The participants then returned to the correct start position for movements, facing toward the linear slide.

Results

VMIQ Analysis. Two independent sample t-tests were conducted on the VMIQ data to test for differences between groups on their reported vividness of internal and external visual imagery. For the external imagery subscale, participants assigned to the Internal imagery group ($M = 47$ ($SD=15$)) and External imagery group (54 (17)) did not differ, $t(16) = 0.875, p > .10$. There was also no difference, $t(16) = 0.898, p > .10$, between the Internal imagery group (43 (12)) and External imagery group (49 (14)) on the subscale of internal imagery.

Manipulation Check. Review of the experimental manipulation check identified two participants who could not adhere to their imagery perspective and two other participants who used kinaesthetic imagery in at least one condition. These four participants were replaced in the data set. When asked to describe what had been imaged, all participants in the External imagery group described performing imagery of themselves in motion, rather than imagery of someone else.

Principal Analysis. The first trial was removed from each condition to minimise task familiarisation effects. Then outliers and extreme values, identified using box-and-whisker plots (Tukey, 1977) were removed from each participant's raw data set. A total of 12 data points were removed from Rehearsal, 12 from Motion, and seven from Colour. Six participants had no outliers. Means and standard deviations were then calculated (see Table 3). Each dependent measure (variable error [VE] and absolute constant error [|CE|]) was analysed using a 2 x 3 (Groups x Condition) ANOVA, with repeated measures on the second factor. A violation of compound symmetry was identified for absolute constant error, where Box's M was significant (p = .009). Subsequently, a square root transformation was applied to the absolute constant error data to remove the violation (Box's M, p = .16).

Table 3. Means and (Standard Deviations) in Rehearsal [Reh], Colour [Col] and Motion [Mot].

	Variable Error (mm)			Absolute Constant Error (mm)			Absolute Constant Error Transformed (mm)		
	Reh	Col	Mot	Reh	Col	Mot	Reh	Col	Mot
Int	11.3 (5.2)	11.8 (5.1)	12.4 (4.8)	25.1 (21.7)	21.0 (15.9)	19.2 (16.5)	4.5 (2.3)	4.3 (1.6)	4.0 (2.0)
Ext	14.8 (2.8)	10.2 (3.7)	10.0 (2.8)	25.9 (16.6)	6.0 (3.2)	12.4 (9.5)	4.7 (2.0)	2.4 (0.7)	3.2 (1.5)

The 2 x 3 (Groups x Condition) mixed model design ANOVA for variable error identified a significant interaction, $F(2,32) = 3.924$, $p = .03$, $\eta^2 = .197$, but no main effect for Condition [$F(2,32) = 1.897, p > .05$] or Group [$F(1,16) = 0.011, p > .05$]. Follow up analysis of the interaction revealed a significant simple main effect for the External group, $F(2,24) = 6.755, p = .005$, but not the Internal group, $F(2,24) = 0.119, p > .05$. All three simple main effect analyses of Condition failed to reach significance ($p > .05$): Rehearsal $F(1,16) = 3.208$, Colour $F(1,16) = 0.544$, Motion $F(1,16) = 1.699$. Tukey's Honestly Significant Difference (HSD) test found that within the External group, the Rehearsal condition had larger errors than the Colour ($p < .02$) and Motion ($p < .01$) conditions. There was no difference between the Colour and Motion conditions ($p > .10$).

The 2 x 3 (Groups x Condition) mixed model design ANOVA for transformed absolute constant error revealed a significant main effect for Condition, $F(2,32) = 3.620, p = .04, \eta^2 = .185$, but no Group [$F(1,16) = 2.033, p > .05$] or interaction effect [$F(2,32) = 2.296, p > .05$]. Tukey's HSD follow-up analysis found that the Rehearsal condition errors were of a significantly greater magnitude than the Colour condition errors ($p < .05$).

Discussion

No interference effects were found in this study. The lack of interference effects could be interpreted as evidence that the cognitive resources provided by the visual association areas V4 and V5 are not shared with visual imagery of movement. It remains possible that other visual stimuli, such as stimuli of the human form, may induce interference effects. Research has indicated that if people manipulate visual information related to body parts, they activate motor processing areas, whereas different areas (particularly visual areas) are activated when objects are manipulated (e.g., Kosslyn et al., 1998).

Errors tended to be greater in the Rehearsal condition. In contrast to the hypotheses, performance was facilitated by the visual stimuli, particularly the colour stimuli. In the Colour condition, both groups showed facilitation of performance as measured by absolute constant error. More facilitation appears to have been experienced by the External imagery group ($M = 2.4$ mm for |CE|) than the Internal imagery group (4.3 mm), although no between groups difference was found.

A clear dissociation between groups was found in the measurement of variable error. The External imagery group produced smaller variable error in both the Colour and Motion conditions, compared to the Rehearsal condition, while the Internal imagery group was unaffected by the colour and motion stimuli. Thus there were two results to consider, namely the facilitation of performance and the dissociation between groups.

Facilitation of Performance

Several possible explanations for the facilitation effects were considered and discounted. One thought was that the conditions might inadvertently have required different attentional demands. This, however, seems unlikely. In both Col. and Mot., the participants were informed that, even though they would not be asked to act on (other than to visually track) or respond to the stimuli, they must attend to the stimuli. Participants also focused on the monitor while doing imagery in the Rehearsal condition. In addition, there is evidence that attending to colours does not produce neural activation beyond area V4 (Bartels & Zeki, 2000).

Dual coding was also discounted as an explanation. Dual coding can facilitate recall when there is a meaningful relation between two items. Certainly there is evidence that visual imagery of movement can bias criterion movement recall (Johnson, 1982), suggesting a meaningful relation between movement and imagery of movement in the form of functional equivalence (see also Sirigu, Duhamel, Cohen, Pillon, Dubois, & Agid, 1996). There is no such relation between viewing a solid colour and visual imagery of movement. Nor would it be accurate to describe the study design as a dual task paradigm.

Convergent processing in the lateral premotor area (e.g., Sakai, Hikosaks, Takino, Miyauchi, Nielson, & Tomada, 2000) has been reported when both timing and response selection were required in a choice reaction time task. Sakai, et al. proposed that the lateral premotor area either integrates timing and response selection, or that it is involved in resource allocation during dual processing. This type of processing is not a viable explanation for the result that performing mental rehearsal while viewing colours (Col.) led to smaller |CE| values than performing mental rehearsal by itself (Reh.). Colour processing would have occurred in V4; there is no evidence that V4 is important to the integration of movement imagery and colour information, or that it allocates resources.

The co-occurrence hypothesis of Polk and Farah (1998) offered another possible explanation. They suggest that extensive exposure to temporally co-occurring stimuli, i.e. letters with letters or numbers with numbers, leads to clusters in neural networks. According to Polk and Farah, these clusters are a result of the social environment producing isolation of the neural clusters, which is not hard wired. For example, when they asked Canadian and U.S. postal workers to detect a letter among numbers or a letter among letters (alphanumeric category task), they found a reduced effect for the Canadian workers. The principle difference between the workers was that the Canadian workers were used to processing numbers and letters at the same time, therefore a letter among numbers did not "jump out" at them. In order for the co-occurrence hypothesis to explain the results of the current study, it would have to be accepted that the cognitive functions involved are not genetically hard wired and therefore the brain areas involved may vary between individuals, based on their social environment. That is to say, most cognitive "functions (e.g., chess playing) that are not old on the evolutionary scale, are not shared with other species, do no provide a clear adaptive advantage, and do not develop automatically without systematic training" (Polk & Farah, 1998, p. 847) do not appear to have localised brain areas dedicated to them. Obviously this notion does not hold for colour and motion processing. It may hold for mental rehearsal, although Shepard (1984) has argued that spatial imagery is constrained by ecological invariants that are genetically encoded. In addition, the use of visual imagery of movement as mental rehearsal is arguably a high level cognitive function and some such functions (e.g., explicit learning [Polk & Farah, 1998]) appear to be localised.

The author proposes an alternative explanation based entirely on the current study: the explanation for the facilitation of performance is that the images were "illuminated" by the visual stimuli. The experiment took place in a dark room and in the Rehearsal condition participants manipulated their imagery while looking at the monitor, which had been turned off. Thus the external environment was dark in Reh. During Col. and Mot., the participant's visual field was filled with a luminant stimulus. This explanation presumes that the effect in Mot. was not due to the motion of the stimulus, but rather to the white screen across which the black dot moved. This stimulation of the visual system may have enhanced the clarity or vividness of the internal representation by allowing participants to "see" more of the image. The author is unaware of any literature suggesting a neural mechanism through which such enhancement may occur.

Dissociation of Internal and External Visual Imagery

The current study found a dissociation between internal visual and external visual imagery. Dissociations between internal and external visual imagery have been reported in the sport psychology literature. White and Hardy (1995) found that external visual imagery had superior effects, compared to internal visual imagery, on the acquisition and execution of tasks that relied on form for their successful completion (e.g., gymnastics). Tasks considered to be open skilled, and depending heavily on perception for their successful completion, (e.g., wheelchair slalom) benefited from internal visual imagery more than external visual imagery. Further support for a dissociation between the effects of internal and external imagery on form based movements have been reported by Hardy and Callow (1999). The linear slide task used in the current study was selected precisely because it does not fall neatly into either task description. Hardy (1997) argued that imagery has a beneficial effect only when it provides useful information that would otherwise not be available. In the current study, the essential information would be target location, which either type of imagery should have been able to supply. Nevertheless, it appears that participants considered the task to be form based, and therefore external imagery had a greater influence on performance.

A purely theoretical explanation for the dissociation is also available, if in fact internal and external visual imagery are processed within the dorsal and ventral visual streams respectively. The spatial coding used during internal visual imagery seems to be egocentric in nature in that the imaged space is coded in relation to the person (reference point) (cf., Sirigu & Duhamel, 2001). Egocentric coding is associated with the dorsal visual stream (Milner & Goodale, 1995), which is in turn associated with the processing of near space (within arm's reach) (Heilman, Bowers, & Shelton, 1990; Vuilleumier, Valenza, Mayer, Reverdin, & Landis, 1998; Weiss, Marshal, Wunderlich, Tellmann, Halligan, Freund, Zilles, & Fink, 2000). Allocentric coding occurs when an object is coded in relation to fixed environmental reference points (e.g., Dijkerman, et al., 1998). The ventral visual stream, which uses allocentric coding (Milner & Goodale, 1995), is associated with processing of far (extrapersonal) space (Heilman, et al., 1990; Vuilleumier, et al., 1998; Weiss, et al., 2000). Thus, it is possible that internal and external visual imagery are processed as near and far space respectively[8].

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[8] I would like to thank the members of the European Brain and Behaviour Society attending the conference at which this research was presented for identifying this explanation.

Summary

The results of the current study indicate that colour and motion stimuli facilitated, rather than interfered with, visual imagery of movement. No theoretical explanation for facilitation could be identified in the literature. It is proposed that the stimuli somehow 'illuminated' the internal representation being used, thereby causing facilitation. No explanation, however, could be provided for how the facilitation occurred. In addition to facilitation, the results indicated a dissociation between internal and external visual imagery in terms of variable error. The visual stimuli differentially affected external visual imagery, resulting in decreased variable error compared to the rehearsal condition. This result seems to suggest that participants considered the task to be form based.

CHAPTER 4

CONFLICTING SOURCES OF SPATIAL INFORMATION IN A DISTANCE REPRODUCTION TASK[9]

Abstract

Previous research has shown that the reproduction of a criterion distance is biased towards previously coded endpoints. The purpose of this research was to illustrate that, in addition to the retention of endpoint information, the presence of conflicting sources of spatial information within a trial causes systematic response biases in distance reproduction. Three experiments were conducted in which participants performed rapid aiming movements on a digitising tablet that translated to movement of a cursor on a computer monitor. The required movement distance was 20 cm. In Experiment 4, the location of the home and target positions on the monitor was fixed while the initial position of the hand varied randomly from trial to trial. In Experiment 5, the change in position of the limb was matched by a corresponding change in the location of the monitor display. In Experiment 6, the initial position of the limb was fixed but the location of the home and target position on the monitor varied from trial to trial. The results of Experiments 4 and 5 illustrated that error varied as a function of the initial position of the limb. This effect was greatest in Experiment 4 where the mapping between the location of the monitor display and limb position varied from trial to trial. There was also an effect of varying the location of the monitor display in Experiment 6 but this was smaller than varying initial limb position in

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[9] This research was presented at the International Congress on Movement, Attention, and Perception in 2002. The research in this chapter is in press: Khan, M.A., Fourkas, A., Franks, I. M., Buckolz, E. and Hardy, L. (in press). Conflicting sources of spatial information in distance reproduction task. *Experimental Brain Research.*

Experiment 4. These findings suggest that both the retrieval of previously specified endpoints and conflicts in the coding of spatial information contributed to the observed response biases in distance reproduction.

Introduction

In numerous everyday activities, people perform rapid movements to specific locations in space (e.g., pointing, reaching and grasping an object, moving a cursor on a computer monitor). In order to perform these goal directed movements, an individual must code and translate spatial information into the appropriate motor commands needed to achieve the task goal (Abrams, Van Dillen, & Stemmons, 1994; Bock & Eckmiller, 1986). There has been considerable debate concerning what spatial information is coded in sensory space and transformed into corresponding parameters in motor space. It has been proposed that the distance from the initial position of the limb to the target is specified by programming the timing and amplitude of force pulses (i.e., distance control) (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Wallace, 1981). In contrast, it has also been argued that the final limb position is coded by specifying an equilibrium point based upon the length-tension relationships of the agonist and antagonist muscles (i.e., position control) (Feldman, 1986; Polit & Bizzi, 1978).

Investigation of the control signal that is specified when performing rapid aiming movements has typically involved variations of either distance or endpoint reproduction tasks. In both tasks, participants are required to produce movements from randomly varying initial limb positions. The goal in distance reproduction tasks is to produce movements of a constant amplitude while the requirement in endpoint reproduction tasks is to terminate movements at a fixed location. If the dominate control signal is distance, than reproducing the same distance from varying initial limb positions would be relatively easy. In contrast, reproducing the same endpoint from different initial limb positions would cause error to vary systematically. Participants would overshoot the target when the initial position is shifted closer to the desired endpoint while they would undershoot when the starting location is moved further from the target. On the other hand, if the dominate control signal is position then performance would be accurate in endpoint reproduction tasks. In a distance reproduction task, however, position control would cause participants to undershoot the desired target when the initial position is shifted towards the endpoint of the previous trial whereas the target would be overshot when the initial position is moved away from the previous endpoint.

In distance and endpoint reproduction tasks, there is a systematic pattern of undershooting and overshooting the target depending on the initial position of the limb (Bock & Eckmiller, 1986; Ilic, Corcos, Gottlieb, Latash, & Jaric, 1996; Imanaka & Abernethy, 1992a; Jaric, Corcos, Gottlieb, Ilic, & Latash, 1994; Jaric, Corcos, & Latash, 1992). The effect of varying starting location on accuracy seems to be less in position than distance reproduction tasks. For example, in a study by Jaric et al. (1994), two groups of participants practiced aiming movements consisting of horizontal right arm elbow flexion movements and were given visual feedback throughout acquisition. One group of participants practiced a distance control task in which they were required to flex their elbow 36 degrees from different initial elbow angles (113 to 137 degrees in 4 degree increments, where 180 was full extension). A second group practiced a location control task in which they were required to end their movements at a criterion angle of 89 degrees from different initial elbow angles (113 to 137 degrees in 4 degree increments, where 180 was full extension). Following acquisition, both groups were first tested on the task they had practiced and then on the task the other group had practiced but without visual feedback. Results showed that both groups reproduced movement endpoints relatively well when tested on the location task. When participants were tested on the distance task, however, the distance travelled increased as initial positions shifted to the right (i.e., elbow angles closer to full extension) and decreased when initial positions shifted towards the left (i.e, elbow angles closer to full flexion). This was the case even for participants who practiced the distance reproduction task. Therefore, regardless of which task was practiced, it appeared that participants coded final positions, and the tendency to reproduce these endpoints caused the distance moved to vary as a function of the initial limb position.

Of interest to researchers has been whether the interference caused from endpoint coding is due to local neuromuscular factors as outlined in equilibrium-point hypotheses or originates at a more central level (see Imanaka, Abernethy, & Quek, 1998). Equilibrium-point models are based primarily on neuromuscular factors such as the specification of tonic stretch reflex thresholds of the muscles (e.g., λ model) (Feldman, 1986). Findings from studies on motor short-term memory, however, have revealed that systematic response biases were present when the criterion and reproduction movements were performed with separate limbs (Imanaka & Abernethy, 1992a). On this basis, it was argued that the retrieval of abstract memory codes was the primary source of interference rather than limb-specific proprioceptive information. Along these lines, Imanaka and Abernethy (1992b) illustrated that cognitive strategies had a significant impact on the degree to which error varied as a function of initial limb position. They showed that distance reproduction was improved when participants were instructed to attend to the initial and end locations of their movements and to take into account changes in start positions from one trial to the next. According to Imanaka and Abernethy, the interference caused by endpoint coding may have been a consequence of automatic processing of irrelevant endpoint information. Bringing this information into conscious awareness through selective attention enabled participants to reduce the interference caused from its automatic processing. Thus, it appears that by simply attending to the changes in the start positions from trial to trial, participants were better able to calibrate target positions in space, which then facilitated the reproduction of the required movement distance from the different initial positions.

Although neuromuscular and cognitive explanations differ in terms of the cause of interference effects, both are based on the premise that systematic response biases observed in the production of a criterion distance arise from the tendency to reproduce previously coded endpoints. Thus, changing the initial position of the limb results in a conflict between the required movement distance and the endpoint retained from the previous trial. The aim of the present research was to illustrate that, in addition to the retention of endpoint information, the presence of conflicting sources of spatial information within a trial contributes to the interference from endpoint coding in a distance reproduction task. These two accounts are not necessarily mutually exclusive, as the retention of endpoint information may be the precursor to conflicts in the coding of spatial parameters. That is to say, in addition to the retention of the previous endpoint, it may be that the previous endpoint introduces a bias in the coding of spatial parameters. In previous investigations of the effects of endpoint coding on distance reproduction, the task was performed without vision of the limb and target (Imanaka & Abernethy, 1992a; Imanaka & Abernethy, 1992b; Jaric et al., 1994; Jaric et al., 1992). Therefore, participants had to rely on visual and/or proprioceptive representations of spatial parameters such as the initial position of the limb and the target. Errors in the representation of the spatial parameters that arise as a result of randomly varying the initial position of the limb could be the cause of systematic biases in movement error.

The processing of visual information dominates other feedback sources (e.g., proprioceptive) and the retention of motor commands (Posner, Nissen, & Klein, 1976). Hence, the manner in which visuo-spatial information is coded would be expected to have a significant impact on the reproduction of a criterion movement distance. In the present studies, the coding of spatial features was explicitly controlled by employing a video aiming task in which participants performed movements on a digitising tablet that translated to movement of a cursor from a home position to a target on a computer monitor. Vision of the cursor was removed during movement execution but the home and target positions were visible throughout the trial. Three experiments were conducted in which participants were required to reproduce a fixed criterion movement distance (see Figure 9). The distance between the home and target positions on the monitor always corresponded to the required movement length but the locations of the monitor display and the initial limb position were varied relative to each other. Thus, the compatibility between distance and location cues was systematically manipulated in an attempt to illustrate that the presence of conflicting sources of spatial information influences the pattern of undershooting and overshooting observed in a distance reproduction task.

In Experiment 4 the display on the monitor remained fixed while the initial position of the limb varied randomly. From the central initial limb position, the production of the required distance corresponded to the location of the target on the monitor. At other initial limb positions, there was a conflict between the required distance and the target location on the monitor. Consistent with past research, it was expected that error would vary as a function of the initial position of the limb. In addition, it was predicted that the conflicting spatial information regarding the target on the monitor and the required movement distance would cause a systematic response bias. The degree to which the production of a criterion movement distance is influenced by location coding was indexed by the magnitude of the slope of the regression line between error and initial position (cf., Jaric et al. 1994; Jaric et al. 1992). If the criterion distance was ideally reproduced, there would not be a systematic relationship between error and initial position. In contrast, if the location on one trial was reproduced on a subsequent trial, the error would be equal to the change in the initial position of the limb. This would result in a slope of the regression line between error and initial position equal to 1. Higher slopes would therefore represent more interference from previous endpoint coding.

In Experiment 5 there was a shift in the monitor display that corresponded to the change in the initial position of the limb. Therefore, the home and target locations

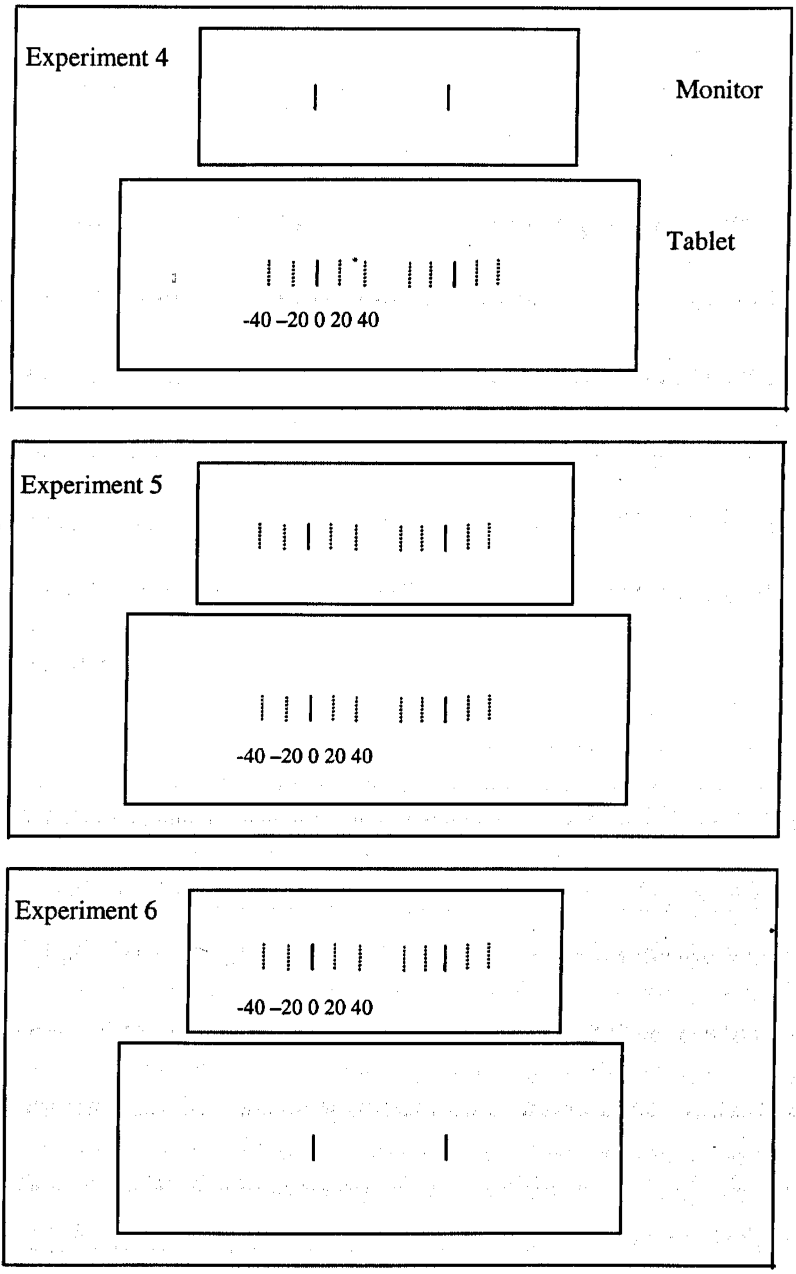

Figure 9. Schematic representation of the experimental set-up showing the location of the home and target positions on the computer monitor and the digitising tablet for Experiments 4, 5 and 6. In Experiment 4 the initial position of the limb was randomly varied while the location of the home and target positions on the monitor was fixed. In Experiment 5 the location of the monitor display was shifted such that it always corresponded to the location of the limb. In Experiment 6 the location of the monitor display was varied while the initial position of the limb was fixed.

on the monitor were always aligned with the initial and final positions of the limb, thus preserving the spatial mapping between the monitor display and limb position. It was expected that the criterion distance would be more accurately produced in this situation since there was no conflict between the location of the target on the monitor and the required movement amplitude. This would be reflected in lower slopes of the regression lines between error and initial position in Experiment 5 than Experiment 4. Since there was no conflict between sources of spatial information in Experiment 5, evidence that interference was caused by the retrieval of previously specified endpoints would be revealed if error still varied as a function of the initial limb position, albeit to a lesser degree than in Experiment 4.

In Experiment 6, the position of the limb remained fixed but the display on the monitor was varied. Thus, similar to Experiment 4, there was a conflict between the location of the target on the monitor and the required movement distance at all but the central location of the display. The influence that conflicting sources of spatial information has on the specification of movement commands would again be illustrated if moving the display on the monitor causes a systematic bias in movement endpoints despite a fixed initial location of the limb. Experiments 4 and 6 involved conflicting sources of spatial information. It was expected that if interference was caused by both the retention of previously coded endpoints and conflicting spatial information, then the degree of interference experienced would be less in Experiment 6 where initial position of the limb was constant across trials.

Methods

Participants

Twenty four university students (ages 18-35) volunteered to take part in the study and were randomly assigned to one of the three experiments. All were right-handed and reported normal or corrected to normal vision. Participants gave their informed consent prior to taking part in the study. Approval for these experiments was obtained from the Ethics Committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor.

Apparatus

Participants sat at a table 70 cm high. They held a stylus with their right hand and performed movements on a SummaSketch III Professional digitising tablet (size = 45 x 31 cm; sampling rate = 120 Hz) placed on the tabletop. Movements were constrained in a left to right direction along a trackway. The position of the stylus was represented by a round cursor (diameter = 0.5 cm) on a Dell Trinitron 19" monitor placed at a height of 30 cm above the table top and 35 cm in front of the participants. There was a one to one mapping between the movement of the stylus and the cursor. The home position was located to the left of the monitor and consisted of a vertical box 2 cm long and 0.2 cm wide. The target was located 20 cm to the right of the home position and also consisted of a vertical box 2 cm long and 0.2 cm wide. Vision of the participant's hand was occluded at all times by an opaque shield placed above the digitising tablet.

Procedures

At the beginning of each trial, participants were instructed to align the cursor with the home position and to then fixate on the target. The requirement to direct their gaze to the target was in keeping with research that has shown on the majority of trials participants fixate on the target before the initiation of limb movement (Abrams & Langraf, 1990). A tone was then presented and participants were required to move a distance of 20 cm as quickly and accurately as possible. It was explained to participants that reaction time was not of interest. The cursor disappeared once it left the home position and did not reappear for the duration of the trial. The home and target positions remained visible throughout the trial. Participants did not receive visual feedback during their movement, but knowledge of results (KR) regarding error and movement time was presented on the monitor at the end of each trial.

Experiment 4. In this experiment, the starting position of the stylus was varied randomly from trial to trial through a range of 8 cm in 2 cm increments (see Figure 9). From left to right, these initial positions were labelled as -40, -20, 0, 20, and 40 mm where the 0 position was aligned perfectly with the location of the home position on the monitor. The location of the home and target positions on the monitor remained fixed. Participants were informed that the initial position of their hand would vary from trial to trial but they were required to reproduce the criterion distance of 20 cm on each trial.

Experiment 5. The initial position of the stylus was varied from trial to trial and was matched by a corresponding change in the location of the home and target positions on the monitor. In keeping with Experiment 4, the initial positions of the limb and the monitor display locations were labeled, from left to right, as -40, -20, 0, 20, and 40 mm. It was explained to participants that the initial position of their limb and the location of the home and target on the monitor would vary in a corresponding manner from trial to trial and that the criterion movement distance was always 20 cm.

Experiment 6. In contrast to Experiments 4 and 5, the initial position of the stylus was fixed throughout the testing session. The locations of the home and target positions on the monitor varied from trial to trial through a range of 8 cm in 2 cm increments. From left to right, these positions were labelled as -40, -20, 0, 20, and 40 mm where the 0 position was aligned with the starting position of the stylus. Note that in Experiment 4, negative initial limb positions implied that the starting location of the limb was to the left of the home position on the monitor while positive initial limb positions meant that the start location of the limb was to the right of the monitor display. In this experiment, negative locations of the monitor display corresponded to the limb being to the right of the display on the monitor while positive locations implied that the limb was to the left of the monitor display. Participants were told that although the locations of the home and target on the monitor varied from trial to trial, they were required to produce a distance of 20 cm from a fixed initial limb position.

At the beginning of each experiment, participants were given 3 trials to familiarise themselves with the task and experimental manipulation. They then performed 200 trials (i.e., 40 at each initial limb position and/or monitor display position) in one testing session. A five minutes rest was given after 100 trials. Within each 100 trial block, the time interval between successive movements was approximately 10 seconds.

Data Reduction

The position of the stylus on the digitising tablet was sampled at a rate of 120 Hz and then filtered using a second-order dual-pass Butterworth filter with a low-pass cutoff frequency of 10 Hz. Instantaneous velocity was calculated by differentiating the displacement data using a two-point central finite difference algorithm. The beginning of the movement was defined as the first point at which the velocity of the stylus was greater than 1 mm/sec. The end of the movement was defined as the point at which the velocity of the stylus fell below 1 mm/sec and remained below that value for 200 msec. The dependent measures of performance were movement time (MT) and constant error (CE). Movement time (msec) was the interval between the start and end of the movement. Constant error (mm) represents the bias in movement endpoints about the target and was calculated from the difference in position of the stylus at the end of the movement and the centre of the target.[10]

For all three experiments, the first 50 trials were removed as practice. The means of the 5 initial limb and/or monitor display positions were then submitted to a repeated measures ANOVA. The results of linear trend analyses and linear regressions are reported since past work has shown linear relationships between

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[10] Analyses of variable error (i.e., within-participant standard deviation in error) revealed no significant effects and are therefore not reported.

constant error and initial position in distance reproduction tasks (Imanaka & Abernethy, 1992b; Jaric et al., 1994).

Results

Experiment 4. The analysis of MT revealed a significant main effect for position, $F(1, 7) = 34.693$, $p < .001$. As indicated in Table 4, MTs decreased as the initial limb positions shifted to the right. There was also a significant main effect for position on CE, $F(1, 7) = 152.987$, $p < .001$. Participants overshot the target from the more leftward initial limb positions while they undershot the target from the more rightward initial positions (see Figure 10a). This produced a slope of the regression line between CE and initial limb position equal to -.46.

Table 4. Mean movement times (and standard deviations) in milliseconds as a function of position in Experiments 4, 5 and 6.

	-40	-20	0	20	40
Experiment 4	473 (86)	456 (78)	445 (73)	435 (78)	420 (79)
Experiment 5	444 (90)	427 (96)	425 (92)	420 (84)	422 (83)
Experiment 6	422 (76)	418 (76)	432 (83)	438 (86)	437 (87)

Experiment 5. A main effect for position on MT, $F(1, 7) = 5.294$, $p < .05$, revealed that movements from the more leftward positions had longer durations than movements from the more rightward positions. Similar to Experiment 4, there was a significant main effect for position on CE, $F(1, 7) = 25.081$, $p < .01$. As shown in Figure 10b, CE decreased as the initial position of the limb and the

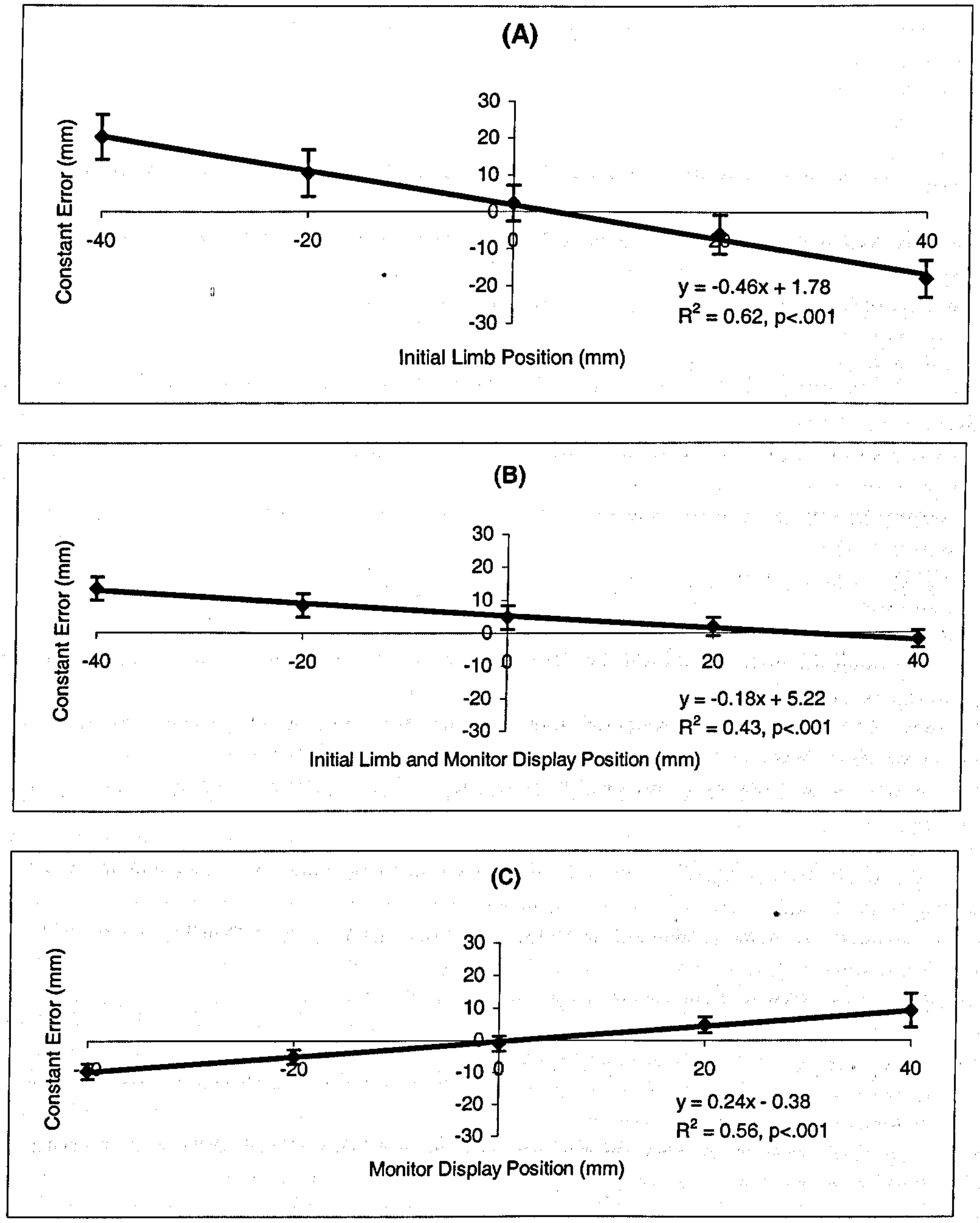

Figure 10. Means and standard deviations of constant errors as a function of initial limb and/or monitor display position in Experiments 4 (a), 5 (b), and 6 (c). In Experiment 4, negative initial positions correspond to the more leftward starting locations of the limb while positive initial positions correspond to the more rightward starting locations. In Experiment 5, negative positions correspond to the more leftward locations of the limb and monitor display while positive positions correspond to the more rightward locations. In Experiment 6, negative positions correspond to the more leftward locations of the monitor display while positive positions correspond to the more rightward locations. Regression equations and correlation coefficients were derived from participant means.

location of the monitor display shifted towards the right, with a slope of the regression line between CE and position equal to -.18.

Experiment 6. In this experiment, the initial position of the limb remained constant but the position of the display of the home and target locations on the monitor was varied. Recall that negative positions corresponded to more leftward locations of the monitor display while positive positions corresponded to the rightward locations. A significant main effect for position on MT, $F(1, 7) = 8.214, p < .05$, revealed that movements took longer to complete as the display on the monitor shifted to the right. The analysis of CE also revealed a main effect for position, $F(1, 7) = 17.543, p < .01$. As shown in Figure 10c, participants undershot the required movement distance when the display on the monitor was shifted to the left while they overshot when the display was shifted to the right. This revealed a positive slope between CE and monitor display position equal to .24. Comparing these results with those of Experiment 4 indicates that in both experiments participants undershot the target when initial limb positions were to the right of home position on the monitor and overshot the target when the initial positions of the limb were to the left of the monitor display.

Comparison Between Experiments. In order to test whether the manipulations between the location of the display on the monitor and initial limb position in the three experiments had different effects on the relation between CE and position, a one way ANOVA was performed on the slopes of the regression lines. The absolute values of the slopes from Experiments 4 and 5 were used since we were interested in the magnitude of the effect of position on CE. The analysis revealed a significant difference between experiments in the slope of the regression lines, $F(2, 21) = 11.1, p < .001$. Post hoc analysis using Tukey's Honestly Significant Difference (HSD) ($p < .05$) test revealed that the slopes were greatest in Experiment 4 ($M = .46$ ($SD = .11$)) while there was no difference between slopes of Experiment 5 (.19) and Experiment 6 (.24). Therefore, varying initial position of the hand while keeping the location of the display on the monitor fixed had the most influence on error. Varying both the initial position of the hand and the monitor display or varying the location of the monitor display while keeping the initial position of the hand fixed caused an equivalent amount of error.

Trial-to-Trial Effects. Based on the work of Weeks, Aubert, Feldman and Levin (1996), we investigated the effects of altering the initial position of the limb and/or monitor display location and the adaptation to these changes by categorising trials as change, repeat and double repeat. Change trials were those in which position varied from that of the previous trial. Repeat trials were cases in which the position remained the same as in the previous trial whereas for double repeat trials the position was unchanged for three consecutive trials. In each experiment, change trials accounted for 70%, repeat trials for 20% and double repeat for 10% of the total number of trials. A repeated measures ANOVA on the regressions slopes in Experiment 4 revealed that there was a significance difference between change and double repeat trials (change $M = -.51$ ($SD = .12$), repeat = -.39 (.14), double repeat = -.31 (.23), $F(2, 14) = 4.072, p < .05$ (Tukey HSD, $p < .05$). In Experiment 5, slopes for the double repeat trials were significantly lower than change and repeat trials (change = -.20 (.10); repeat = -.19 (.19), double repeat = -.05 (.13)), $F(2, 14) = 3.688, p < .05$ (Tukey HSD, $p < .05$).

Although no significant effects were observed on the slopes in Experiment 6, a similar trend was apparent (change = .24 (.17), repeat = .21 (.23), double repeat = .17 (.15)), *F*(2, 14) = 0.631, *p* > .05.

Discussion

Past research has shown that when participants were required to reproduce a criterion distance, movement endpoints were systematically biased when the initial position of the limb varied from trial to trial (Imanaka & Abernethy, 1992b; Jaric et al., 1994; 1992). It has been suggested that participants code the final position of the limb on a particular trial and the tendency to reproduce this endpoint causes error to vary as a function of the initial position of the limb. Endpoint coding has been well accounted for in equilibrium models of limb control which elaborately describe the neuromuscular mechanisms which govern position control (e.g., Feldman, 1986). Other researchers have highlighted the contribution of higher cognitive factors such as the retention of abstract memory codes and attention to specific spatial cues as potential sources of endpoint interference (Imanaka & Abernethy, 1992b). In the present research we intended to extend these findings by showing that conflicts in the coding and translation of visuo-spatial information contributes to the systematic response biases observed in a distance reproduction task.

Consistent with past research, the results of Experiment 4 indicated that manipulating the initial position of the limb resulted in a systematic pattern of undershooting and overshooting the target. In this experiment, the initial position of the arm was varied but the location of the home and the target positions on the monitor remained fixed. This created a conflict between the display on the monitor and the position of the limb at all but the central initial limb position (i.e., 0 mm). In Experiment 5, the home and target positions on the monitor always corresponded to the initial and required end locations of the limb. Thus, there was no conflict between the location of the target on the monitor and the desired movement distance. Eliminating this conflict significantly improved the reproduction of the criterion distance with the slopes of the regressions lines being significantly reduced compared to Experiment 4.

It is also possible that the effect of varying initial position on error was less in Experiment 5 than Experiment 4 because aligning the monitor display with limb position enabled participants to more accurately calibrate proprioceptive sources of information. Proprioceptive localisation in limb matching tasks has been shown to improve when participants are given visual information of either the indicator limb (van Beers, Sittig, & Denier van der Gon, 1996) or the target limb (van Beers, Sittig, & Denier van der Gon, 1999a). Therefore, representations of initial and desired final limb locations in the present studies may have been more accurate when they were aligned with the home and target positions on the monitor. However, although our results showed that the effect of initial position on constant error varied between experiments, variable error was not affected. Therefore, it appears that performance was dictated primarily by the presence or absence of conflicting sources of information rather than the acuity of spatial localisation.

The results of Experiment 6 provided further evidence that the coding of visuo-spatial information on the monitor influenced the reproduction of the criterion movement distance. In this experiment, participants were required to reproduce the criterion movement distance from a fixed initial limb position; the neuromuscular commands should have remained unchanged from trial to trial. Therefore, the systematic bias in movement endpoints appears to have been caused by varying the home and target positions on the monitor. This effect was somewhat similar to that observed when the visual field is displaced through wedge prisms. Distorting vision by prisms has been shown to alter proprioceptive localization of a limb in the direction of its visually displaced location (Warren, 1980; van Beers, Sittig, & Denier van der Gon, 1999b)[11]. Also, the final positions of aiming movements are systematically biased when movements are produced very rapidly (Smith & Bowen, 1980). Looking through prisms displaces all information in the visual field by the same amount. The perception of locations in space would have been altered but the perceived criterion movement distance would not have been affected (Abrams et al., 1994), similar to the manipulation of the display on the monitor in our experiments where the distance between the home and target positions remained constant. Therefore, the finding that error was systematically biased indicates that participants coded location information on the monitor and this interfered with the reproduction of the criterion distance.

While the present results illustrated that the systematic pattern of undershooting and overshooting was due in part to processing of conflicting sources of spatial

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[11] van Beers et al. (1999b) have shown that for two dimensional movements, the perceived location does not fall on a straight line between the proprioceptively and visually perceived locations but is based on the direction-dependent precision of the two modalities.

information, evidence also points to the retention of previously specified endpoints as a source of interference. Although the compatibility between visual information on the monitor and limb position was preserved in Experiment 5, there was still a significant effect of varying the initial position of the limb. Also, the influence of changing the spatial mapping between the monitor display and the limb position was greater when the initial position of the limb was varied (Experiment 4) compared to when the location of the monitor display was varied (Experiment 6). These findings suggest that shifting the initial position of the limb resulted in interference that was in addition to the effect of manipulating the spatial compatibility between the monitor display and limb position. Researchers have suggested that the coding and retention of endpoints could take the form of equilibrium points in the neuromotor system (Feldman, 1986) and/or abstract spatial codes in short term memory (Imanaka & Abernethy, 1992a). Although the current data does not allow us to specify the mechanism by which endpoints were coded, the results clearly demonstrate that the production of the criterion distance was subject to interference caused by the retrieval of previously specified endpoints.

Further evidence that interference was caused from the short term retention of movement parameters stems from the finding that the relation between initial limb position and error was strongest on “change” trials, after which participants showed partial adaptation when the limb position was repeated. Weeks et al. (1996) reported similar patterns of interference and adaptation when the load characteristics of the limb were varied randomly. However, while one trial adaptation was evident in their work, participants did not fully adapt in the present experiments even when the initial limb position was repeated twice. The reason for this may be that only two load conditions were used in the experiments of Weeks et al. while five different starting locations were used in the present work. Therefore, it was probably easier for participants to make the appropriate adaptations between two compared to five levels of a manipulated variable.

Although we have elaborated on the effect of coding retinal information from the display on the monitor on distance reproduction, extraretinal signals may also be contributing to the pattern of results reported here. Extraretinal information is provided from the oculomotor commands used to bring the eyes to the target and proprioceptive feedback from the eye muscles. These signals may include a composite of distance and position information and have been shown to play an important role in the accuracy of aimed limb movements (Abrams & Landgraf, 1990; Abrams, Meyer, & Kornblum, 1990). Binsted and Elliott (1999) have shown that biasing eye movements through optical illusions have an effect on limb movements depending on the temporal relation between the movement of the eye and limb. They reported that when participants were required to fixate on the home position prior to limb movement, and eye and limb movements were initiated by a common signal, the final position of the eyes but not the limb were biased by a Muller-Lyer illusion. Both the endpoints of eye and limb movements were offset, however, by the illusion when participants were instructed to fixate on the target well in advance of limb movement initiation. It may be that when the eyes were fixated on the target well before limb movement initiation, extraretinal signals about eye position had sufficient time to influence the final position of the limb. Also, distance information from the eye movements may have decayed in the interval between the movement of the eyes and the movement of the limb. Along these lines, van Donkelaar, Lee and Drew (2000) have shown that when movements of the eyes and limb are initiated by a common signal, and are required to move to the same target from different initial positions, the distance travelled by the limb varies directly with the amplitude of the saccade. In the present research, participants were instructed to fixate on the target before movement initiation. Although this instruction was based on research that has shown participants fixate on the target prior to limb movement, it may be that when there is a sufficiently long delay between the eye and limb movement, the final location of the limb is biased towards the position of the eyes. It is possible that if saccade and limb movements were initiated in closer temporal proximity, the amplitude of the saccade may have facilitated the production of the criterion distance.

Summary

The present results indicated that participants coded locations in space and this interfered with the production of the criterion movement distance. Consistent with previous research, the finding that error varied as a function of the initial position of the limb indicated that interference was caused by the retrieval of previously specified endpoints. The effect of varying initial limb position was greater when the spatial compatibility between the monitor display and limb position was varied. Also, varying the position of the monitor display while keeping limb position fixed resulted in systematic biases in error. These findings suggest that, in addition to the retrieval of previously coded endpoints, conflicts in the coding of spatial information contributed to the observed response biases in distance reproduction.

CHAPTER 5

GENERAL DISCUSSION

Summary of Main Findings

The use of secondary concurrent tasks, to make inferences about neural structures involved in visual imagery of movement, led to a number of unanticipated findings. It had been presumed that if imagery and a secondary task involved the same brain structures, and therefore the same cognitive resources, then interference effects on performance would be found. The visual imagery was performed with eyes open, which may or may not have been consistent with the personal preference of the individuals participating, and all participants assigned to external imagery imagined the self, rather than someone else, in motion. Chapter 2 (study 2) provided some evidence that visual imagery of movement involves neural structures associated with motor performance. The results suggested that visual imagery, performed concurrently with a finger sequence task, led to a greater magnitude of error than visual imagery alone. The lack of between groups differences may have resulted from a confound by kinaesthetic imagery.

Study 2 also indicated that when the concurrent finger sequence task was performed, the combined visual and kinaesthetic imagery affected performance differently than when no concurrent task was performed. In the Sequence condition, the combined imagery led to smaller errors than did visual imagery, while in the Rehearsal condition no difference was found. This result may have been due to finger sequencing and kinaesthetic imagery sending conflicting signals to the peripheral motor system. An alternative, or additional, explanation may be that finger sequencing and kinaesthetic imagery activated the same neural structures. This 'central' interference explanation is problematic, however, in that finger sequencing did not affect visual imagery alone in the same manner as it affected the combined use of visual and kinaesthetic imagery. This suggests that there is a resource that visual imagery may use, but that kinaesthetic imagery and finger sequencing do not, for which there is no obvious theoretical explanation.

Chapter 3 (study 3) presented evidence that the slow motion and colour stimuli facilitated, rather than interfered with, performance. This was reflected in two main findings. The magnitude of error was smaller for both the Internal and External imagery groups when participants viewed colour while simultaneously performing mental rehearsal compared to when participants performed mental rehearsal by itself. In addition, the External imagery participants had significantly smaller variable errors when they viewed colour, or watched a slowly moving dot, while simultaneously performing mental rehearsal compared to performing mental rehearsal by itself. Variable error did not differ across experimental manipulations for the Internal imagery group. The reason for the facilitation, as well as the dissociation in performance between the Internal and External imagery groups as measured by variable error, is unclear.

Chapter 4 looked at the phenomena of interference effects that are typically found during distance reproduction tasks. In the past, interference effects have generally been attributed to the coding and storing of the previous movement endpoint in either an abstract mental representation or as neuromuscular commands. In addition to these between trial effects, the series of three studies also investigated whether conflicting spatial information within a trial causes interference effects. It was presumed that a systematic response bias would result if conflicting spatial information causes interference.

A significant amount of interference was experienced in all three studies, indicating that both between trial effects (coding and storing of the previous endpoint) and within trial effects (conflicting spatial information in the visual and motor sensory spaces) affected the reproduction of the criterion distance. Comparison of the slopes showed that the largest amount of interference was experienced in study 4. This finding was attributed to the presence of both conflicting information and the retention of previous movement endpoints. In study 4, the home and target position on the monitor had remained fixed, while the initial position of the limb varied across trials. The slope in study 5 was significantly less than study 4 because there was no conflicting information. Shifts in the home and target positions on the monitor were matched to shifts in the initial limb position. The fact that interference was still found in study 5 must therefore have been due to the retention of previous movement endpoints. The significantly smaller slope in study 6, compared to study 4, was presumably due to the presence of conflicting information but absence of the effect of previous movement endpoints. In study 6, the home and target positions on the monitor varied across trials, while the initial position of the limb remained fixed.

Theoretical Considerations

The results of the imagery studies (Chapters 2 and 3) highlight the fact that we know very little about where and how visual imagery of movement operates in the brain. None of the original hypotheses were supported. These results were somewhat surprising given the extensive body of literature regarding the neural underpinnings of visual imagery (for reviews, see Farah, 1988; Denis & Kosslyn, 1999). On the other hand, visual imagery and visual imagery of movement used for mental rehearsal may not be equivalents of one another in that visual imagery of movement is a "goal directed" activity. That is to say, people engage in visual imagery of movement in order to accomplish a physical task while visual imagery is generally used to facilitate the recall of information and to make judgements. The purpose of the imagery involved differs and it may be that different transformations are applied to information according to the intended outcome of the task. When there is intention to act, visual information is processed differently from when there is attention to action but no intention to act (cf., Colby, 1996).

The studies reported in Chapter 4 provide evidence that both visual and proprioceptive information can induce the distance-location interference effect. While models of movement control based predominately on neuromuscular mechanisms (mass-spring models, equilibrium point models) may be able to account for the results of studies 4 and 5, they cannot account for the results of study 6. These models specify movement in terms of desired final limb position (e.g., Feldman, 1986; Polit & Bizzi, 1978). Final limb position is achieved when the limb (mass) is held in a stable position by the opposing agonist and antagonist muscles (springs). Changing the tension in the muscles causes the limb to move. Distance-location interference occurs when the limb is biased by the previous final limb position. In study 6, however, desired final limb position was constant due to initial limb position being constant across trials. Nevertheless, manipulation of visual information was sufficient to cause interference.

Allocentric and Egocentric Coding. The use of allocentric coding may explain some of the results of the imagery studies (Chapters 2 and 3). Ferrel, Orliaguet, Leifflen, Bard and Fleury (2001) demonstrated that the nature of the environmental reference affects the effectiveness of allocentric coding. They manipulated the environmental reference via contextual cues: a white frame around the target, a familiar sized object in the background (a playing card), or a dark surround. Participants performed pointing movements on a digital tablet that were translated into movement on a computer monitor. Perceived movement amplitude was manipulated on the monitor. In the vision condition, hand displacement was recorded by a camera and a graphic representation of their hand was seen to move on the monitor, versus the no vision condition. Actual vision of the hand was occluded. The target could not be coded in direct relation to the person, therefore egocentric coding could not be used. The use of a frame or familiar object led to smaller spatial errors and faster movements in the vision condition, and faster movements in the no vision condition, than did the dark surround. If we assume that participants coded the hand on the monitor as "their own", as it appears they did, then this study provides evidence that people can code themselves as an object moving in the environment. Thus, it is conceivable that in study 3 (Chapter 3) the lighted monitor (Colour and Motion conditions) served as a contextual cue 'framing' the imagined space and enhancing allocentric coding, whereas a dark surround was provided by the Rehearsal condition. This may explain why external imagery was more affected by the visual stimuli than was internal imagery. Furthermore, the lack of between group differences in studies 1 and 2 (Chapter 2) may have been due to the absence of enhanced allocentric coding via contextual cues in the External imagery group.

When movement is delayed, coding can switch from egocentric to allocentric (Milner & Goodale, 1995). Rossetti, Lacquaniti, Carozzo and Borghese (unpublished, cited in Rossetti, 1998) asked people to point to memorised targets on a computer monitor. After delays of 0 or 500 ms, responses were aligned with target direction (forward). Delays of 1 to 8 seconds resulted in responses aligned with the target array (left-right). The interpretation provided by Rossetti et al. was that at delays up to 500 ms, endpoints were coded with an egocentric reference frame centred on the start position. Delays of 1 second or longer caused endpoints to be coded in extrapersonal space, with an external reference frame dependent on the visual context of the experimental set up. Thus, if in actual movement tasks spatial coding switches from egocentric to allocentric after approximately 1 second, then it must be asked whether it is possible for internal imagery of movement – which clearly, involves a delayed response – to use egocentric coding.

Wraga, Creen and Proffitt (1999) have argued that egocentric coding is employed during certain types of imagery. Wraga et al. (1999) performed a review of the imagery literature in which imagining oneself rotating around an object to a new viewpoint, or imagining a part of oneself rotating (e.g., hands – see Kosslyn et al., 1998), was defined as egocentrically coded imagery (relative reference frame). "The front-back and right-left axes of the relative frame 'belong' to the observer.

When the observer moves, the entire relative frame moves with her: It is biologically impossible to move the relative frame in a piecemeal fashion (Wraga et al., 1999, p. 261)." Any difference between egocentric coding in images and egocentric coding during on-line motor control (cf., Milner & Goodale, 1995) was not addressed. Considered with Ferrel et al. (2001) and Rossetti et al. (unpublished) research, the Wraga et al. (1999) review suggests it is possible that both egocentric and allocentric coding may be employed during manipulation of internal representations.

Similar to the studies reported in Chapter 4, Ferrel, et al. (2001) asked participants to perform movements on a digitizing tablet that were translated into movement on a computer monitor. Based on Ferrel, et al. it can be assumed that the home and target positions presented on the monitor in studies 4, 5, and 6 (Chapter 4) were allocentrically coded, as the visual information could not be coded in direct relation to the limb. That is, the coding would be allocentric because the participants were not pointing at the target *per se.*

If the home and target positions had been pointed to *per se*, then the coding would likely have been egocentric, even if vision of the limb were occluded (Carrozzo, McIntyre, Zago & Lacquanti, 1999). Carrozzo et al. asked people to point at virtual targets presented in three-dimensional space. Vision of the target was always available. Carrozzo et al. determined the type of coding participants used based on the amount of response variation that was recorded along different axes. In the Seen condition (vision of the hand available) the axis of maximum variability was oriented with the line of sight (labelled 'viewer-centered';

egocentric coding by the eyes and head). In the Unseen condition (hand occluded) the axis of maximum variability was aligned with the body (labelled 'body-centered'; egocentric coding by the shoulder or arm). Thus, in Carrozzo et al. the visuomotor transformation was direct, while in the studies 4, 5 and 6 the transformation was indirect suggesting the use of allocentric coding.

Strengths of the Research Programme

Sport psychologists have become increasingly interested in the neural activity which accompanies imagery (e.g., Murphy, 1994). With the development of the field of cognitive neuroscience, such consideration is more easily accomplished. The research contained in this thesis focused on motor control, in particular the control provided via imagery, from a multidisciplinary approach. Of particular interest was the application of knowledge regarding the visual and spatial processes involved in movement. Through utilisation of the cognitive neuroscience literature, behavioural studies addressing the mechanisms involved during visual imagery, manipulated via mental rehearsal, were conducted and clearly illustrated that there is much to learn about the topic. In many ways, however, that was to be expected considering the highly exploratory nature of the research.

While Chapter 4 itself does not make reference to the cognitive neuroscience, the general introduction and general discussion of this thesis attempt to tie the experimental chapters together. All the research contained herein used manual aiming tasks. Thus, one can presume that characteristics inherent to the tasks, e.g. the nature of the spatial coding involved, would be highly similar. The relation between ego-/ allocentric coding and theories of distance – endpoint interference is a relatively unexplored topic. It is likely, however, that the studies in Chapter 4 involved allocentric coding of the target in relation to the limb (cf., Ferrel et al., 2001).

Another strength of the current research was the experimenter control exerted during the imagery studies. Imagery is an introspective task. It is therefore important to ask people about the content of their imagery (Murphy, 1994). The use of manipulation check questionnaires in the imagery studies provided systematic feedback regarding what participants imaged. In allowing participants the opportunity to describe their imagery, condition specific feedback was gathered regarding image content. Through review of the descriptions it was possible to ascertain that all external imagery participants imagined themselves in motion, rather than someone else. In addition, it was possible to verify that participants employed the correct perspective, and the use (including extent) or non-use of kinaesthetic imagery. The manipulation checks identified several participants that did not adhere to experimental instructions; these participants were subsequently replaced, ensuring that only those participants who followed the imagery instructions were retained for analysis.

In the imagery studies, participants viewed videotape recordings illustrating the required internal and external visual imagery perspectives. The use of video definitions for the imagery perspectives provided a "common language" that the participants and the experimenter could use. The video was used in addition to the imagery questionnaire (VMIQ), minimising errors in understanding by providing both written and visual clarification of the type of spatial coding to use. In addition, the use of the video definitions increased the experimenter's confidence that participants were accurately reporting whether or not they had adhered to their assigned perspective.

Limitations of the Current Research Programme and Future Directions

Imagery Studies. There were several limitations to the research reported in Chapter 2. Methodologically, an apparent confound of kinaesthetic imagery presented the largest problem. In essence, in the initial analysis of study 2 there were six, rather than two, groups: internal visual imagery alone, external alone, internal plus kinaesthetic, external plus kinaesthetic, internal but not sure about kinaesthetic, and external but not sure – all with different group sizes. Initial pilot work (prior to study 1) and study 1 itself had not indicated that people would be particularly inclined to use kinaesthetic imagery. Nevertheless, only eight people, out of 24, in study 2 were certain that they had used no kinaesthetic imagery. It was not possible to do a between groups comparison of the "did not use kinaesthetic imagery" participants because six of them were External imagery participants, and only two were Internal imagery participants. The small *n* and unequal sample sizes meant that the original analysis – a comparison of only internal visual and external visual imagery perspectives – could not be carried out on the eight people.

The secondary analyses of study 2 did, however, show some evidence that visual imagery was interfered with by finger sequencing. The finger sequence task should have activated multiple brain structures in the motor and sensorimotor cortices (e.g., Roland et al., 1980; Catalan et al., 1998), making interpretation of the results somewhat difficult. Instructions to not use kinaesthetic imagery would minimise concerns about the role of the sensorimotor cortex as well as isolating the effect on the motor cortex to the influence of visual imagery. Thus, it would be worthwhile to conduct the study again with participants given instructions not to use kinaesthetic imagery. In addition, it might be interesting to re-run the experiment with specific instructions to use kinaesthetic imagery in an attempt to replicate the cancelling effect found in the Sequence condition.

The facilitation effects reported in Chapter 3 were attributed to the illuminating of the internal representation. There is no obvious theoretical explanation for why, much less how, the effect occurred. Thus the interpretation requires further investigation. In addition to attempting to replicate the finding, it would be useful to re-design the study so that imagery was performed with different lighting conditions. For instance, if the facilitation was simply caused by the presence of light, then a study performed with the lights on should have similar results. If, however, the results were due to contextual cues provided by the monitor (cf., Ferrel et al., 2001), then performing the imagery while looking at a white wall should have a different effect; if the effect on external imagery were reduced while the effect of internal imagery remained the same, then there would be some evidence that allocentric coding was being used in external but not internal imagery.

Additionally, the types of motion and colour stimuli could be manipulated. That is, was facilitation caused simply by stimulation of a visual area? If so, then also watching a stick figure run across the screen (rather than a dot moving) should facilitate performance – even though the figure clearly suggests human movement, which may therefore require processing of conflicting movement information.

Including two external imagery conditions in future research, one with imagery of the self in motion while the other is imagery of someone else, in addition to an internal imagery condition, would also be useful. It may distinguish whether or not there are differences in brain areas involved in the two forms of external imagery, and possibly extend the findings that 'of self' imagery involves the dorsal stream (e.g., Sirigu & Duhamel, 2001), while 'of someone else' involves ventral stream structures (e.g., Deiber et al., 1998). If there were a difference (e.g., 'of self' using the dorsal stream and 'of someone else' using the ventral stream), then the question would again be raised of how imagery manipulated in the ventral visual stream influences the motor system. It would also allow internal visual imagery to be compared to the different external imagery conditions, revealing differences and similarities in neural processing. If differences in processing are accompanied by differences in performance, then it may increase the understanding of how visual imagery manipulated for mental rehearsal affects the motor system. For example, it may be possible to explain the wheelchair slalom result of White and Hardy (1995) where the internal imagery group was more accurate while the external group was faster.

It was assumed that measures of spatial error would be affected by imagery, but perhaps temporal accuracy measures would have been revealing. The current study design required that the participant first reach for the handle and then to move promptly to the target. Thus participants were not instructed to move as quickly as possible, and the possibility that some may have used a degree of online programming cannot be excluded. Had the design been different, e.g. the hand on the handle at the start of each trial, then it would have been possible to measure simple reaction time. This would indicate how much pre-programming was occurring and if the amount of pre-programming differed with different imagery perspectives. Combined with the measures of spatial accuracy, the content of the program could be assessed. Instructions to move as quickly and accurately as possible would also allow for analysis of speed-accuracy trade-offs occurring with different imagery perspectives, extending the work of White and Hardy (1995) and Sirigu et al. (1996).

The imagery research was highly exploratory. In selecting a place to begin investigating the brain structures involved in visual imagery of movement it was hypothesized that internal imagery is processed in the dorsal visual stream and external in the ventral visual stream. The hypotheses were based on where the visual system employs egocentric and allocentric coding. However, there was no investigation of the possible third stream described by Milner and Goodale (1995). The third stream, with connections from both the dorsal and ventral visual streams, has been implicated in the manipulation of imagery (Milner & Goodale, 1995). It is thought that this third stream is not purely visual (Milner & Goodale, 1995); it appears to receive input from all the perceptual modalities. As such, an appropriate interference task could not be isolated. On the other hand, the imagery research reported in this thesis demonstrated little in the way of interference effects; thus, it is possible that a different behavioural task could be designed to investigate involvement of the third stream. The added difficulty, however, is the stream's apparent multi-modal nature; as a result, hypothesizing whether internal, external, or both forms of visual imagery are manipulated there may be challenging.

Distance Reproduction Studies. The instructions of studies 4, 5 and 6 included the instruction to fixate the eyes on the endpoint presented on the monitor. The conclusions, therefore, are constrained by that instruction. However, different pointing responses are induced when people accompany arm movements with saccadic eye movements, as opposed to fixating their eyes. For instance, van Donkelaar (1997) asked participants to point to targets; limb movements were either the same distance as saccadic movements, 10 degrees shorter than saccadic distance, or 20 degrees shorter. If vision of the limb was occluded, responses requiring longer saccadic distances were accompanied by longer arm movements. That is, undershoot decreased as saccadic distance increased. This effect disappeared when vision of the limb was available, and when participants remained fixated on the initial eye position. When vision of the limb was available participants were quite accurate. When participants fixated, they overshot the target independently of the initial eye position. Fixated eye movements were also reported to accompany greater movement amplitude in a study investigating visual and remembered targets (van Donkelaar & Staub, 2000). Movement amplitude was significantly longer when people fixated on the target than when the eyes were allowed to move with the hand, regardless of whether the target was visible or remembered. Thus, it may be interesting to repeat studies 4 and 6 (Chapter 4) to see if the level of interference is affected when the eyes are allowed to move with the arm. Recall that in study 4, the home and target positions on the monitor remained fixed while initial position of the limb shifted from trial to trial. In contrast, the home and target positions varied from trial to trial while initial position of the limb remained constant, in study 6.

The current studies were also limited by their inability to distinguish between whether people used abstract representations (cf., Imanaka & Abernethy, 1992b) or neuromuscular commands (cf., Feldman, 1986) to accomplish the task. This inability resulted from the fact that every abstract representation (provided it was present) was followed by a physical response. It may be possible to disentangle the two explanations by using a 'go – no go' paradigm. On some trials a signal would be given indicating the participant should move to the target ('go'), while on other trials a signal would be given indicating no movement should be made ('no go'). Participants would not know what type of trial they were to perform until the signal occurred, thus requiring that they prepare to move on every trial. If interference was still found when a 'no go' trial was followed by a 'go' trial, then this would indicate that an abstract representation was the cause as there would be no previous endpoint to recall.

Other Future Directions

The use of brain imaging (e.g., positron emission tomography [PET], functional magnetic resonance imaging [fMRI], electroencephalography [EEG]) can provide a broad picture of the brain areas involved in different tasks. Of particular interest to the study of motor control are the visual, somatosensory, motor and prefrontal (executive) areas. A wide range of issues raised in the discussion of the current research could be investigated with these techniques. What are the structures shared by visual imagery of movement and finger sequencing? What happened during facilitation? Where do internal and external visual imagery operate? What differences are there between 'of self' external imagery and 'of someone else' external imagery?

Brain imaging, however, has its limits. Although both PET and fMRI produce high spatial resolution images (1-3 mm) of the brain, they have poor temporal resolution (Martin, 1999). In order to measure brain activity during performance with PET, radioactive water or glucose must be injected. Thus, PET is considered an invasive technique. Temporal resolution is low, as blood flow is slower than neural transmissions. In contrast, fMRI is considered non-invasive. It detects functionally induced changes in the magnetic field: increases in blood flow leads to increases in oxygen levels, which in turn changes the magnetic properties of haemoglobin. Temporal resolution is low, as on average only four images per second can be obtained. EEG is also non-invasive. It has high temporal resolution in that it can record neural activity in real time, but it has poor spatial resolution.

Another option is the use of transcranial magnetic stimulation (TMS). TMS allows the experimenter to induce a transient functional disruption in a targeted set of neurons in order to determine what those neurons do and when (Pascual-Leone, Walsh, & Rothwell, 2000). For instance, Ganis, Keenan, Kosslyn and Pascual-Leone (2000) applied TMS over the primary motor cortex during mental rotation of pictures of hands. They found that primary motor involvement was specific to the hand (but not the foot) representation, and that the involvement was late (650 ms after stimulus onset) rather than early (400 ms). That is to say, only applying TMS to the hand representation at 650 ms after stimulus onset had an effect. TMS can also be used to examine functional connections within the brain when employed in combination with brain mapping techniques, e.g., PET (Paus, 1999).

While neuroimaging techniques have varying degrees of spatial and temporal resolution, Walsh and Rushworth (1999) argue that TMS has the advantage of having "functional resolution". It can disrupt function for as little as a few tens of milliseconds with a spatial resolution of about 1 centimetre. While neuroimaging shows activation is correlated with a behavioural event, TMS can demonstrate the necessity of the brain area for the task because it directly interferes with the neural tissue (Walsh & Rushworth, 1999). For example, Lee and Donkelaar (2002) used TMS to determine where relative target size information is processed. TMS was applied over the dorsal or ventral visual stream during pointing movements to the central circle within the Ebbinghaus illusion display (a centre circle of constant size surrounded by a series of larger, or smaller, circles). The results indicated that target size was processed in the ventral visual stream and affected the motor system via the prefrontal cortex, bypassing the dorsal visual stream.

Concluding Remarks

To summarise, this thesis was based on an interest in understanding the visual and spatial processes underpinning intentional movement. Some of the processes were passively encoded from the environment while others were actively encoded through imagery. At the outset, the integration of the cognitive neuroscience literature with the imagery of movement literature appeared rather straightforward. As with all exploratory research however, there were many surprises. These surprises forced considerable re-evaluation of the way the author thinks about visual imagery of movement, how it affects the motor system, and how it relates to concurrent motor control. Along the way, a new perspective on allocentric coding became apparent in terms of interpreting the results of the distance reproduction tasks. In short, the work involved in completing this thesis has on a personal level been both challenging and rewarding while on a professional level it has been highly developmental.

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Appendix A

Experimental Manipulation Check

Participant # _______ Perspective ________________ Date ______

Please read the following questions/statements about your imagery, supplying the most accurate and concise responses that you can.

Mental Rehearsal Alone

1. I was able to adhere to my assigned perspective. Yes No

2. It was difficult to maintain the imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

3. I was able to begin the imagery from the start position.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

If you marked one of the last three options, where did the imagery begin?

____

4. I would have preferred to use the other imagery perspective. Yes No

5. I experienced some physical feelings or sensations (kinaesthesis) during my imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

Please describe the kinaesthesis:

____

____

6. Please describe what you imaged.

____

____

____

Mental Rehearsal Plus Finger Sequencing

1. I was able to adhere to my assigned perspective. Yes No

2. It was difficult to maintain the imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

3. I was able to begin the imagery from the start position.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

If you marked one of the last three options, where did the imagery begin?

____

4. Mental rehearsal was harder with finger sequencing than without.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

5. The mental rehearsal interfered with my finger sequencing.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

6. The finger sequencing interfered with my mental rehearsal.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

7. I would have preferred to use the other imagery perspective. Yes No

8. There was a component of kinaesthesis (feeling, physical sensation) to my imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

Please describe the kinaesthesis:

____

____

9. Please describe the images formed.

____

____

____

Math Problems

1. I found myself doing mental rehearsal when I was doing the math problems.

Yes No

If yes, please describe what you imaged.

____

____

Any other comments about my imagery.

____

____

Any other comments about the study.

____

____

Appendix B

Experimental Manipulation Check

Participant # ______ *Perspective* ______________ *Date* ______

Please read the following questions/statements about your imagery, supplying the most accurate and concise responses that you can.

Mental Rehearsal Alone

1. I was able to adhere to my assigned perspective. Yes No

2. It was difficult to maintain the imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

3. I was able to begin the imagery from the start position.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

If you marked one of the last three options, where did the imagery begin?

4. Please describe what you imaged.

5. I would have preferred to use the other imagery perspective. Yes No

6. I experienced some physical feelings or sensations (kinaesthesis) during my imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

Please describe the kinaesthesis:

Mental Rehearsal Plus Viewing Colours

1. I was able to adhere to my assigned perspective. Yes No

2. It was difficult to maintain the imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

3. I was able to begin the imagery from the start position.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

If you marked one of the last three options, where did the imagery begin?

____

4. Please describe what you imaged,

____

____

____

5. Mental rehearsal was harder while viewing colours than without.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

6. Colour viewing interfered with my mental rehearsal.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

7. I would have preferred to use the other imagery perspective. Yes No

8. There was a component of kinaesthesis (feeling, physical sensation) to my imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

Please describe the kinaesthesis:

____

____

Mental Rehearsal Plus Smooth Movement Tracking

1. I was able to adhere to my assigned perspective. Yes No

2. It was difficult to maintain the imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

3. I was able to begin the imagery from the start position.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

If you marked one of the last three options, where did the imagery begin?

____

4. Please describe what you imaged.

____

____

____

5. Mental rehearsal was harder while smooth movement tracking than without.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

6. Mental rehearsal interfered with my smooth movement tracking.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

7. Smooth movement tracking interfered with my mental rehearsal.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

8. I would have preferred to use the other imagery perspective. Yes No

9. There was a component of kinaesthesis (feeling, physical sensation) to my imagery.

Strongly Agree Agree Not Sure Disagree Strongly Disagree

Please describe the kinaesthesis:

____

____

Any other comments about my imagery.

____

____

____

Any other comments about the study.

____

____

____