The Experience of Action: Intention and Attention

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Abstract

'Motor awareness' can be defined as any reportable knowledge available about a movement. This topic has received little attention from psychologists. This thesis aimed to establish suitable methods for measuring motor awareness. Two methods were developed; first, movement reproduction, a kinematic approach measuring the spatial details of participants' awareness, second, temporal judgements, a cognitive approach measuring awareness of movement duration. Both were found to be sensitive and appropriate measures.

Movement reproduction was used in Experiments 1, 2 and 3 to investigate awareness of online corrections in pointing movements. In Experiment 1 slow, intentional corrections were reproduced accurately, whilst fast, automated corrections showed attenuated awareness. Anti point errors were an exception to this pattern. These automated corrections entered awareness as accurately as intentional movements. It was proposed that intention plays a major role in the extent to which a movement enters motor awareness and that errors also trigger a supervisory attentional system. Experiments 2 and 3 combined movement repetition with saccadic suppression. Perceptual and motor awareness were found to dissociate; participants reproduced movement corrections made in response to target jumps, even when perceptually unaware of the target jumps themselves. Experiment 3 attempted to disrupt online corrections with TMS, but no basic effect of TMS was found.
Experiment 4 used a variant of temporal discrimination to investigate awareness of saccades. Again a dissociation of awareness was found, the intentional, planning component of the saccade entered awareness, whilst the automated component was subject to the chronostasis illusion. Experiments 5, 6 and 7 then combined Verbal Time Estimation with attentional cueing tasks. Participants were aware of the attentional effects on their RT when caused by endogenous cues, but not when caused by exogenous cues.

Finally, a model was proposed in which motor awareness receives inputs from both an intentional system and error detecting circuits.
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The Extent of My Personal Contribution

In accordance with the requirements of the University of London, the extent of my personal contribution to the work in this thesis is specified as follows.

I was funded by the BBSRC; Committee Studentship 99/B1/S/05282, at the ICN, UCL. My primary supervisor was Dr. Patrick Haggard and my secondary supervisor was Prof. Jon Driver. I made major contributions in the design of all the studies reported here. The majority of the computer programming, data collection and data analysis was performed by myself. The exceptions to this are listed below.

Robert J. van Beers contributed considerable technical expertise for the programming in Experiments 1, 2 and 3.

Experiment 4 was conducted in collaboration with Kielan Yarrow; we both contributed to the design, data collection and analysis. Data from this experiment was also included in KY's thesis for the degree of PhD (neurological studies, UCL).

This thesis is entirely my own original work and no other person should be held accountable for its contents.

Helen Johnson
1. Conscious awareness of movements

To what extent are we aware of our movements? What do you know about how you tie your shoelaces? Or how you drive a car? Clearly, we know that we are doing or have done these things. Yet, when it comes to introspection and verbalisation it is our overall action plans, our intentions and goals, that are readily available to us, while the details of our motor control remain largely unconscious. However, we would not claim to be entirely unaware of our movements. We know when we have moved, we know if we initiated a movement or if something else moved us, we know whether we made the movement that we intended.

The relationship between our awareness of movements and the intentions that precede them is known to be a complex one and when disturbed, the consequences can be devastating. Frith, Blakemore and Wolpert (2000) argued that delusions of control in schizophrenia were the result of a failure to appropriately process expected sensations during a limb movement. Conversely, they noted that anarchic hand syndrome occurs when patients fail to be aware of their intention to move, whilst remaining aware of the movement itself. Consequently, patients no longer feel in control of their limb (Ay, Buonanno, Price, Le, & Koroshetz, 1998). It has also been noted that this disorder is disproportionally disturbing for the patient (Persaud, 1999). This led Persaud to argue that as a movement can occur without conscious awareness of intent, the latter is simply a useful illusion that prevents people being distressed by their own movements.
However, this theory is far from sufficient. It may explain awareness of intent, but it offers no explanation as to why awareness of movement exists. Clearly such awareness does exist, as otherwise anarchic hand patients would not know that they had moved at all. What purpose then does motor awareness serve? Is it a necessary aspect of normal movement?

**Perceptual awareness, motor responses and intentions**

Pélisson, Prablanc, Goodale and Jeannerod (1986) initially proposed a distinction between motor control and conscious processes. They found that efficient movements could be made without awareness of either intention or movement. They showed that participants could automatically correct an ongoing movement, apparently without being aware that they had done so. They did this by making a target move after participants had already begun to reach out towards it. By timing the target shift to coincide with the initial saccade, the resulting retinal error is ascribed to saccadic undershoot rather than to the target shift. This leaves participants unaware that the target has moved. However, participants were just as efficient at pointing to the final target location as when there had been no shift. They concluded that these automated corrections occurred without entering consciousness.

What then is the purpose of motor awareness? The clinical effects detailed by Frith et al (2000) have shown what can happen if the normal relationships between awareness of intention and movement breakdown. Yet, Pélisson et al (1986) have shown that awareness is not a necessary feature of efficient movement.
In order to gain more understanding of the mechanisms underlying awareness researchers have begun to look at its functions. It may be that there is some critical difference between those movements of which we are aware and those of which we are not. If so, this could be the key to understanding major psychological questions about free will and agency, as well as being a step towards fathoming the purpose of consciousness itself.

The early on-line corrections investigated by Pélisson et al (1986) have continued to be a rich source of information. Paulignan, Mackenzie, Marteniuk and Jeannerod (1990) whilst investigating other aspects of early corrections, found that perceptual awareness dissociated from motor ability. They used an overt target shift time locked to the participant's movement onset. When the participant was later asked to report when the target shifted, they consistently reported that it happened later in their trajectory than it actually did. This was despite being able to correct the movement far earlier in the trajectory and within around 100ms. However, as this dissociation was not the main purpose of the experiment it was not considered fully, but simply reported as an anecdotal finding.

Castiello, Paulignan and Jeannerod (1991) argued that this dissociation between perceptual awareness of a stimulus and the motor response to it was evidence of two distinct processing streams. As such they undertook to investigate the effect reported by Paulignan et al (1990) further. They adapted the original experiment to look specifically at this potential dissociation. Participants were placed in a darkened room and presented with three pieces of vertical, translucent dowel. One dowel was illuminated from beneath. The participants' task was to reach out and grasp the
illuminated dowel. On 20% of trials, within a few milliseconds of the movement starting, the illumination would unexpectedly shift to another dowel. When this happened participants were required to correct their trajectory and grasp the newly illuminated dowel. In addition, participants were required to give a vocal response 'Tah!' as soon as they were aware of the target shift.

Like Paulignan et al (1990), Castiello et al (1991) found that participants began to correct their trajectories around 100ms after the target shift. This was more than 200ms faster than the reaction time for response initiation at the start of the trial. However, the vocal response occurred some 420ms after the target shift, at least 300ms slower than the correction to movement.

With additional control experiments Castiello et al (1991) were able to demonstrate that the delay was not caused by interference between the motor and verbal tasks. This was done by running the task under two additional conditions. In one only the motor response, i.e. the online correction, was performed. In the other, no movement was made but the verbal response was still given to the target shift. No difference was found between the measures in these single tasks and those when both tasks were completed. As such, Castiello et al (1991) ruled out an interference locus of the effect.

They concluded that conscious awareness of a target shift only occurs after the stimulus has undergone further processing, either additional to or different from that required for motor control. This takes a significant amount of time and so the experience of awareness is significantly delayed. Conversely, motor correction is an automated on-
line process that is rapidly recalculated as part of the ongoing movement.

Consequently, it shows a greater temporal delay.

However, whilst this gives some insight into the relationship between stimulus awareness and motor correction, it does not add a great deal to our knowledge of motor awareness or indeed of motor corrections themselves. There is a fundamental difficulty with these studies in that they are measuring behaviour in one modality and awareness in another. If we are interested in what a participant knows about their movement, then any measure of awareness must be a measure of motor awareness and not of perceptual awareness. That is, Paulignan et al (1990) and Castiello et al (1991) both asked participants to report their awareness of the target whilst measuring their motor performance. Whilst one might expect these to be highly correlated, qualitatively they are very different aspects of the task.

A further attempt to consider the status of these early online corrections was made by Day and Lyon (2000). They avoided a direct measure of awareness and instead considered the extent to which the responses were modifiable by the participant’s intent. They noted that the work of Castiello et al (1991) and Pélisson et al (1986) indicated that early online corrections were both automated and unconscious. This led them to ask 'to what extent would such an automated movement then be modifiable?' They asked participants to complete a standard double-step task, i.e. one in which the target shifts during the ongoing movement. However, in some conditions participants were instructed to move against rather than with the target. That is, if the target jumped right, instead of correcting their trajectory to reach it at its new rightward location, they
were to point left. In this anti point task, the intention of the participant was therefore pitted against the natural and automatic response to follow the target.

Again, Day and Lyon (2000) found that participants could respond to a target shift with an early change in their trajectories. In the standard pro point condition most (95%) of the movement corrections occurred at less than 150ms as previously reported (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1990; Castiello, Paulignan, & Jeannerod, 1991). However, the anti point trials showed a more complex pattern. 24% of trials showed correction latencies of over 160ms. However more critically, in the remaining 76% of trials where the correction latency was less than 160ms, the early corrections were in the wrong direction. That is, participants first made an erroneous pro point response, which was then inhibited and followed by an additional correction in the appropriate direction.

Day and Lyon (2000) concluded that this was evidence of two classes of response. The first was the automated, unconscious response that led to early online corrections as investigated by Paulignan et al (1990) and Castiello et al (1991). This automated response could not be adapted for use by tasks other than those with a direct stimulus-response mapping. That is, it could not be modified to encompass an indirect task. Hence, in the anti point task, in which the stimulus had first to be transformed before the appropriate response could be executed, any early corrections seen were in the erroneous direction. Second, there was a slower, modifiable response that could be adapted to the participant's will according to the experimental instructions. However, despite this dichotomy, they noted that the two responses could not be due to entirely
independent systems. Whilst early corrections in the anti point task could not be modified when they occurred, they were successfully suppressed in almost 1/4 of trials.

In addition, Day and Lyon (2000) considered the timing of the later responses. They argued that for these responses to be truly voluntary the late correction would have to come after conscious awareness of the target shift. Yet, whilst the late, modifiable responses were considerably delayed in relation to the automated responses, they still occurred before the participant would be conscious of the target shift. That is, the late corrections in the Day and Lyon (2000) study were around 200ms after the target shift. However, Castiello et al (1991) found conscious awareness of such a shift had a latency of around 400ms.

Consequently, Day and Lyon (2000) concluded that this made it unlikely that were two separate systems. Instead, they proposed a theory based on early ideas by Hughlings Jackson (1932). Here, rather than having two distinct systems, one automated and one modifiable, a continuum is suggested. Responses would be distributed along it with greater or lesser levels of automaticity.

If however, this theory is correct, where does it leave explanations of conscious awareness? We know now that early online corrections can not only be unconscious (Pélisson et al 1986), but that they are automated to such an extent that they can only be suppressed and not modified by will alone (Day and Lyon, 2000). Would that suggest that awareness is also a continuum? Do movements enter awareness to a greater or lesser extent depending on the automaticity of the response?
The above studies cannot answer these questions as none directly study motor awareness itself. Castiello et al (1991) and Pélésson et al (1986) for example, both looked at the relationship between target awareness and motor response, rather than motor awareness per se.

**A theoretical framework for studying motor awareness**

As can be seen from the above experiments little research has been conducted directly on motor awareness. However, the following three experiments have attempted to address this. All have looked at ways in which different components of an action can be dissociated and studied the resultant effects. Before considering these studies it may be helpful to first consider a possible theoretical framework within which these studies can be compared.

First it is necessary to define some of the terms that are used in this field, as there can be considerable variation as to the precise meaning of some concepts. In this thesis ‘motor awareness’ is defined as any reportable knowledge a participant has about their movement. It would not, for example, include knowledge about the stimulus or event that caused a movement. Motor awareness and movement awareness are used interchangeably. However, throughout this thesis distinctions will be made between actions and movements. Here, an action is considered to be a primarily psychological concept. It is defined as an overall plan to achieve a goal. A movement however, is primarily considered to be a kinematic event; the specific motor output that is implemented to achieve that plan. Critically, a single action can be broken down into a number of parts. The three main components of interest here are:
- Intention: what you aim to achieve
- Movement: the physical motor output that you implement
- Perceptual Consequence: what you believe you achieved

In a real world situation these factors will bind to form an overall action representation. When a successful action has occurred all three will be congruent. However, when some aspect of the plan fails there is internal incongruence between the sub-parts. For example, if the expected consequence is not achieved it may be said that a ‘mistake’ has been made. However, in some situations this can be immediately rectified, such as by making an online correction to a movement to ensure the goal is achieved.

If this is the case, then by experimentally manipulating incongruence within an action plan, it should be possible to study the extent to which each component impacts upon motor awareness.

The first such recent study was conducted by Fourneret and Jeannerod. Participants were asked to draw a line in the sagittal plane on a graphics tablet (Fourneret & Jeannerod, 1997). By use of a mirror and a computer screen participants saw a projection of the line being drawn rather than their hand and the actual line. In addition, on some trials a constant bias was imposed on the perceived line causing the projection to deviate leftwards or rightwards even when the actual path remained straight. Participants unconsciously corrected their path so that the projection of the line remained straight. The result of this was an unconsciously erroneous (deviating) movement in which the intention, to draw a straight line, appeared to have been successfully achieved.
Two measures of awareness were taken. In one condition they presented participants with a series of lines and asked them which one was closest to the trajectory they had just followed. In the other, they were asked to draw the path again from memory, but this time with their eyes closed to preclude the use of visual feedback. They found that participants were largely unaware of the corrections they had made to their movements in order to counteract the perceptual intervention. That is, they consistently reported that they had completed a sagittal and relatively straight trajectory, even when the actual path deviated by as much as 10°. This finding held whether participants reported their movement verbally through comparison with visually presented paths or by physically repeating it (Fourneret & Jeannerod, 1997).

However, within this global effect Foumeret and Jeannerod (1997) also found considerable individual differences. This led to them separating their participants into two post hoc groups. This separation was based not on the extent to which participants recognised their deviations, but on their perception of the direction of them. When a deviation was reported, albeit a slight one, group 1 consistently claimed they had moved in the direction opposite to their actual trajectory. Conversely, group 2 claimed they had deviated in the direction they actually had moved in. Despite this, neither group showed significant awareness of the extent of their deviations.

Two findings however remain clear from this study. First, much like the lack of stimulus awareness demonstrated in previous reports (e.g. Pélisson et al 1986), participants also show a lack of motor awareness about their movements. The second
more serendipitous finding is that when intention and feedback on performance are placed in direct contradiction the resulting effects can be complex and unexpected.

Fink, Marshall, Halligan, Frith, Driver, Frackowiak and Dolan (1999) attempted to image the neural effects of such a contradiction. They used Luria's (1969) bimanual coordination task in which people, usually frontal lobe patients, are asked to clench and unclench their hands. This is done either in phase (left and right hands both clenched, then both unclenched) or out of phase (left hand clenched, right hand unclenched, etc). Fink et al (1999) then superimposed a mirror over one of the participant’s hands. This resulted in them seeing a mirror image of the opposite hand. Consequently, whilst performing the task out of phase the visual feedback was that of being in phase. Participants then underwent a PET scan whilst performing this task in all possible conditions.

Fink et al (1999) reported two main findings. First, participants’ introspective reports of how peculiar the task felt varied across conditions. In particular, when performing the task out of phase and seeing it in phase, they reported a significantly greater sense of peculiarity. That is, participants were aware that the movement was correct, yet the perceptual consequence was erroneous. Second, they found significant activation of the right dorsolateral prefrontal cortex (DLPFC) during this mismatched condition.

Fink et al (1999) concluded that the right DLPFC was responsible for monitoring motor intention and ensuring the correct plan was in place despite the contradictory visual feedback. They also argued that right midventral prefrontal cortex, as opposed to dorsolateral areas, were responsible for monitoring proprioceptive and visual
congruence. In addition, they claimed that it was the detection of incongruence that led to conscious awareness, as recorded by participants' reports of 'peculiarity'.

Finally, in an unpublished study Paulignan, Roy and Jeannerod (2000) recently attempted to adapt Castiello et al’s (1991) paradigm to look specifically at motor rather than perceptual awareness in early online motor corrections. They asked participants to complete a perturbation trial and then point to where their hand had been when they had begun to correct their movement. Unfortunately, there were a number of problems with this study. First, it assumed that participants could not only access information about their position at discrete points throughout an ongoing movement, but also that they can explicitly isolate and report any one of those points at will. Second, in Paulignan et al’s (2000) study, participants showed very late corrections. This would suggest that the movements elicited were not the early, automated responses that they claimed to be investigating (cf Castiello et al 1991) but the late, modifiable responses identified by Day and Lyon (2000). The reasons for this remain unclear.

Despite these difficulties Paulignan et al (2000) found that their participants began to correct their movements earlier than the positions that they later indicated. They concluded that participants showed delayed motor awareness of their own correction.

Such findings add another level of complexity to the relationship between intention and awareness. Previous researchers have shown under a variety of conditions (Pélinson, Prablanc, Goodale, & Jeannerod, 1986; Castiello et al., 1991; Fourneret & Jeannerod, 1997; Paulignan, Roy, & Jeannerod, 2000) that participants are largely unaware of their movements. Yet, Fink et al (1999) clearly demonstrated that they can be aware.
However, if we consider these findings within the framework discussed earlier the key difference is whether there is a mismatch between intention and consequence (see Figure 1.1). In Paulignan et al’s (2000) task, participants successfully completed the intended action. That is, their task was to reach out and grasp the target regardless of any location change. In Fourneret and Jeannerod's study (1997) the movement may have been erroneous but the intention, to draw a straight line, appeared to have been successfully achieved. In Fink et al's (1999) task the movement was correct, yet the perceptual consequence was erroneous.

**Figure 1.1 Schematic representation of the experimental findings.**

<table>
<thead>
<tr>
<th></th>
<th>Intention</th>
<th>Movement</th>
<th>Perceptual consequence</th>
<th>Motor awareness?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paulignan et al (2000)</td>
<td>congruent</td>
<td>congruent</td>
<td>congruent</td>
<td>NO</td>
</tr>
<tr>
<td>Fourneret &amp; Jeannerod (1997)</td>
<td>congruent</td>
<td>incongruent</td>
<td>congruent</td>
<td>NO</td>
</tr>
<tr>
<td>Fink et al (1999)</td>
<td>congruent</td>
<td>congruent</td>
<td>incongruent</td>
<td>YES</td>
</tr>
</tbody>
</table>

This dissociation suggests that when an action plan appears to have been successfully completed the details of the movement do not get passed on to the systems responsible for awareness, even if the actual movement requires some modification during execution. However, when the consequence of the movement is not what was intended, the action plan has failed. At this point, the details of the movement must be made available to supervisory attentional systems in order to correct the error. It therefore seems probable that this information is being stored at the time of execution so that it is available if needed. However, as it is not always readily available, it is also likely that
the storage is a short term facility and that the movement representation is highly susceptible to decay and/or over writing.

**Intention and awareness**

So far we have considered evidence that was largely collected within a motor control framework. However, other researchers have also approached aspects of this problem. In particular, Libet (1985) looked at the chronometrics of intentional actions. Libet, Gleason, Wright and Pearl (1983) measured participants’ *bereitschaftspotential* (BP), a slow negative potential that can be recorded using electroencephalography (EEG). This potential precedes voluntary movements and peaks immediately before the movement begins.

The participant’s task was to make a freely-willed volitional movement, at a time of their choosing. At the same time, they were asked to watch a fast moving clock and judge what ‘time’ it was when various events occurred. Events to be judged included the time at which they first felt the ‘urge’ to move and the time at which they actually began to move. Libet et al (1983) then compared the ‘time’ of these events with the BP onset and peak. They found that brain activity began some 200ms before the participants reported the ‘urge’ to move. In addition, participants reported that they actually began to move 86ms before they actually did. Libet et al (1983) concluded that what appeared to the participant to be conscious awareness of the intention to move was actually the result of pre-existing cortical activation reaching a certain level. That is, the brain ‘knew’ it intended to move before the participant was consciously aware of it.

This finding, as well as the method used, caused considerable controversy (Näätänen, 1985; Stamm, 1985). However, the second conclusion, that participants reported that
they began to move before they actually did, has received little attention. Yet this finding appears to be an early measure of motor awareness. It suggests that participants are not only aware of their movements but that they localise them as having occurred earlier than they actually did.

This finding is in direct contradiction of the work of Paulignan et al (2000) and is somewhat incompatible with that of Fourneret and Jeannerod (1997), who all found that participants were not aware of their movements. Nor is it easily explained with the theory of internal incongruence detailed above. However, there is a further critical difference between the Libet et al’s (1983) task and those of Paulignan et al (2000) and Fourneret and Jeannerod (1997). Libet et al’s participants’ movements were entirely volitional.

It is not yet clear how the status of the movement, whether entirely volitional (Libet, Gleason, Wright, & Pearl, 1983), entirely stimulus driven (Paulignan et al., 2000) or some combination of the two, will affect participant’s awareness of their movements. However, it would appear that this is an area that would benefit considerably from additional research.

Efferent binding

Although the model presented in Figure 1.1 is presented here as a conceptual aid, rather than a theoretical model, there is further evidence for the suggested components and the relationships between them.
Haggard, Aschersleben, Gehrke, Prinz (2002) proposed a system called efferent binding. They suggested that this process could theoretically occur in much the same way as perceptual binding occurs in vision. That is, efferent binding would cause intentions to be associated with both the desired consequence and the appropriate motoric output required to achieve it. Together these would be ‘bound’ to produce an overall action plan. They went on to argue that this is primarily a motor learning relationship. That is, by binding intention and consequence in this way, we are able to learn whether the intervening motoric output is appropriate (i.e. achieved the desired consequence) or whether it requires some additional refinement. Haggard et al (2002) acknowledged that this process need not be conscious. However, they also argued that even if consciousness is not actually necessary, it is likely to be closely related.

Haggard at al (2002) went on to hypothesise that if the efferent binding process existed, it was likely to show similar properties to visual perceptual binding. In particular, they argued that the sub components of the action should attract one another temporally, as visual objects do spatially. They tested this by asking participants to make time judgements of events (cf Libet et al 1983) whilst performing a variety of tasks. These tasks could essentially be broken down into stimulus onset or movement onset in both volitional and stimulus-response tasks. That is, the perceived relative timing of a beep could be considered when it occurred either as a consequence of a volitional response or as a stimulus that must be responded too.

Haggard et al (2002) found that in both conditions (volitional movement followed by stimulus, or stimulus followed by response), the two events were perceived as having occurred closer to one another than when either occurred alone. That is, the first event,
whether stimulus or movement, was perceived as occurring later and the second event as occurring earlier. They concluded that these shifts were evidence of the attraction effects between the sub components of an action plan as a result of efferent binding.

In addition, Haggard et al (2002) conducted an additional control experiment in which tones and responses occurred in a linear temporal fashion, but with no causal relationship. They found no evidence of stimulus and response attraction in this condition. They therefore concluded that it was the relationship between the events and not the events themselves that cause the temporal attraction reported above.

The concept of efferent binding within an action plan has since been investigated further. Haggard and Clark (2003) used transcranial magnetic stimulation (TMS) to elicit involuntary movements in participants. In a further condition participants were asked to make volitional movements as and when they felt like it. In both cases the actual movement would trigger an auditory tone to occur. Again by using the temporal measure devised by Libet et al (1983) it was possible to measure participants’ perceived timing of both the response and the tone. They again found that when a tone followed a volitional movement the perceived timing of both shifted together. That is, the movement was perceived as occurring later and the tone earlier. However, no such shift was seen when the movement was elicited by TMS and not by volition. They concluded that whilst the previous study (Haggard et al, 2002) had shown that a causal relationship was necessary for efferent binding to occur, it was not sufficient alone. That is, in order for a causal movement and its resulting stimulus to be temporally bound in this way, an intention to make the causal movement must first exist. However,
none of these experiments explored the consequences of incongruence between the components.

Clinical disorders

Finally, cognitive neuropsychologists have argued that investigating patients with clinical disorders can provide insight into the normal functions of the underlying systems (Ellis & Young, 1991). Therefore, having looked at what is currently known about awareness and its associated effects in the normal population it is worth considering the most relevant clinical disorders of awareness in more detail. There are numerous clinical dissociations of awareness, such as delusions of control in schizophrenia (Frith, Blakemore, & Wolpert, 2000; Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003). However, the disorders most relevant to this thesis are: anarchic hand syndrome, split brain patients and certain forms of anosognosia.

‘Alien’ or ‘anarchic’ hand syndrome can be a ‘pure’ deficit, presenting with no other neurological deficits. However, more commonly it is found in patients with general degenerative disorders such as dementia. Essentially the patient presents claiming that some or all of the time they have no control over one hand. This is usually the left hand of a right-handed patient (Ay et al., 1998). Other disorders can lead to patients losing control of their limbs (e.g. dyskinesia, hemibalismus) but in these cases the patient still recognises that the actions is ‘theirs’ (Ay et al., 1998). Anarchic hand sufferers however, do not recognise that they initiated the movement. That is, they have no conscious awareness that the limb’s behaviour, ‘belongs’ to them.
As they are unable to recognise the limb as 'self' they confabulate that it must be
'other'. This can result in claims that it is possessed or has a 'mind of its own'. Despite
the unwanted movements of the limb being largely innocuous, if irritating, many
patients perceive the hand as having malevolent intent (Persaud, 1999). This is an
interesting response in itself. Patients could perceive the movements as being
uncontrolled but without intent however, despite anarchic hand patients not claiming
control of the movement, they do claim that it has 'intent'. There must therefore, be
some qualitative difference between being subjected to uncontrolled reflexive
movements and those experienced by anarchic hand patients.

Additional evidence for this comes from similar deficits found in 'split-brain' patients.
'Split-brain' patients have undergone a complete callostomy, in which the corpus
callosum, which normally joins the two cerebral hemispheres, is severed. This
procedure is usually performed as a last resort to control intractable epilepsy. These
patients are typically tested by presenting stimuli to only one hemisphere and asking the
patient to report what they saw or felt. Due to hemispheric asymmetries various
reporting methods, including verbal, pointing or drawing, are used.

In Joseph’s (1988) classic paper, two split-brain patients are reported: one who had
developed bilateral motor control (1c) and one who had not (2c). Joseph claimed that
1c showed little or no right hemispheric capabilities, including being unable to respond
to the experimenter’s hand as well as to pictorial or semantic information. However, he
performed normally when stimuli were presented to either central vision or the right
visual field. 2c however, was able to raise his left hand in response to the
experimenter’s hand as well as making some responses to pictorial or semantic stimuli.
However, the most striking difference between the two patients' was in their motor control. Whilst 1c had developed bilateral control with his left hemisphere, 2c had not. Consequently, 1c was able to consciously, or volitionally, control his left extremities, whilst 2c could not. Joseph (1988) concluded that, ‘2c demonstrated the presence of two independent forms of conscious awareness’ (p.770), one in each hemisphere.

Consequently, his left and right limbs could simultaneously engage in independent purposeful behaviour, whilst 2c was only consciously aware of the intentions of the left hemisphere/right limbs. For example, his legs may try to walk in different directions or his hands switch a television both on and off. As with patients with anarchic hand syndrome, Joseph reported that 2c was often distressed by his left limbs. He would swear at them, strike or punch them and on occasion would physically fight to control his left hand with his right.

Despite 2c being entirely unaware of any intent or control over the left hand, Joseph (1988) demonstrated that its behaviours were not random but goal directed. For example, if differing stimuli were presented to his two hands and 2c was required to identify them by pointing, his left hand would point to the item presented to it. 2c’s right hemisphere would then verbalise that this was wrong and he would try (unsuccessfully) to force the hand to point to the stimulus felt by the right hand. As 2c was unaware that any stimulus had been presented to his left hand, he was also unaware of its ‘reasons’ for pointing to a particular item. As such, it would seem likely that anarchic hands also have ‘reasons’ for initiating a particular action, even though the patient is entirely unaware of them.
If this were the case, what kind of ‘reason’ would lie behind such behaviour? The evidence from Joseph’s (1988) 2c patient, is a goal-directed reason. That is, a stimulus driven automated response, similar to the automated stimulus driven corrections seen in normals (Pélisson et al., 1986; Day & Lyon, 2000; Paulignan et al., 2000). As discussed earlier, such movements can be just as efficient without awareness of either the movement or the intent.

However, there is also another disorder that presents quite the opposite symptoms, anosagnosia, or the lack of awareness of a deficit. Here, the patient will typically present with a serious disability. Yet, when questioned they will claim to be perfectly well. In addition, they will frequently produce outlandish confabulations to justify their beliefs, (e.g. see (Weiskrantz, 1997). Ansoagnosia can occur in any illness. Patients who deny being blind (Weiskrantz, 1997) amnesic (McGlynn & Schater, 1989) and partially paralysed (Bisiach, 1988) have all been reported.

It is the partially paralysed patients that offer the more interesting insights here. Shallice (1991) reported one such patient with left-sided hemiparesis and ansoagnosia. When asked to make a movement with his left hand the patient would fail to move. When the experimenter questioned this, the patient would respond with comments such as, ‘just give me time to proceed from thought to action’ (Shallice, 1991, p397). The patient clearly believed that he intended to move and he appeared to be willing the action to occur. However, when no motor output was produced he would simply confabulate a response rather than acknowledge that he was actually unable to move. However a further patient, who presented with similar deficits, demonstrated a different strategy.
When asked to perform a task with his left hand, he would respond appropriately. However, instead of using the left hand as requested, he would use the right. When questioned about this he would either deny the behaviour or claim he had simply made a mistake.

What then, does this tell us about motor awareness in the normal population? According to the framework presented earlier (Figure 1.1), we would predict that there would be an incongruity within the action plan when the appropriate consequence failed to occur. This incongruence should then lead to conscious awareness of the overall failure of the action plan, and hence the disability. However, here we see two coping strategies in order to reduce that incongruence and thereby avoid the associated awareness. The first patient believes that the action plan has not failed, it just has not been completed yet. The second believes that the action plan has been successful as the consequence (i.e. the task being completed) has occurred, but with an incorrect motor response (i.e. the other hand). This provides further evidence that incongruence is a major feature in motor awareness. Where such incongruence is present without awareness, patients have to go to extreme lengths of confabulation in order to justify their beliefs.

Summary

This chapter has reviewed a wide-ranging body of literature. In particular, the experimental evidence of dissociations between awareness and motor control has been examined. This included the earlier studies that looked at stimulus awareness and the more recent studies that have tried to directly tap motor awareness. In addition, more peripheral aspects of motor control were reviewed. This included studies on awareness
of intention and the chronometry of action binding. Finally, clinical disorders of motor awareness were considered in some detail.

The main conclusion reached was that motor awareness is a complex and under researched topic. It has been found to differ widely across a variety of movement types and for a variety of reasons within those types. This includes automated movements that never enter awareness, modifiable movements that sometimes enter awareness and incongruous movements that always enter awareness. In addition, it is suggested that volitional movements can enter into awareness even when a motorically similar stimulus driven response does not.

In such an under researched area virtually every aspect requires further investigation. However, a theoretical framework was proposed within which to consider future studies of motor awareness. In particular, it will help to identify which manipulations of congruity between the components of an action plan remain to be investigated. Finally, the effects of congruity manipulations on motor awareness need to be considered separately across stimulus driven and volitional actions.
2. Experiment 1: Awareness of online motor corrections

Introduction

It has been suggested that there are two routes to action; a fast automated route and a slower controlled route (Frith & Done, 1986). It has been argued that the two routes are mediated by two systems, with the slower option requiring additional attentional input. One critical feature of the fast route is that the response is directly mapped to the stimulus.

Previous studies have also shown that participants are able to make fast automated corrections to an ongoing movement (Castiello et al., 1991; Pélisson et al., 1986; Day & Lyon, 2000). These corrections occur when a target changes position during an ongoing movement. The result is a double-step movement, with an on-line correction to the new location. The timing of these corrections is now believed to be as early as 100-150ms (Paulignan et al., 1990; Castiello et al., 1991). These studies were considered in more detail in the previous chapter.

Pélisson, et al (1986) showed that participants could correct their movement to a new location, without being aware that the target had shifted. Here the target moved during the initial saccade. However, participants were equally efficient at pointing to the final
target location as when there had been no shift in its location. They concluded that fast corrections occurred without entering perceptual awareness.

Day and Lyon (2000) investigated the relationship between participants' intentions and on-line corrections. Two conditions were tested. Pro point, when participants had to move with the target and anti point, where they moved in the opposite direction. They found that the intention to move away from the light could partially suppress the early corrections. When participants had to anti point fewer early corrections were seen than when pro pointing. In addition, when an early correction was present it was invariably in the wrong direction. That is, it was an erroneous pro point response that was subsequently inhibited. Day and Lyon concluded that the early response was automated and could not be adapted to a response that was not inherently stimulus bound. A similar result was reported by Pisella et al (2000). Here a target colour change, rather than an anti point, was used to induce an intentional response. Again they found that participants made erroneous automated corrections to a target displacement. These errors were not seen in response to a target colour change, suggesting a dissociation between these two mechanisms of movement correction.

Castiello, et al (1991) attempted to directly investigate participants’ perceptual awareness in a double-step paradigm. They asked the participants to make a vocal response, ('Tah!') as soon as they were aware that the target had moved. Castiello et al found that the verbal responses occurred some 300ms after the movement correction began. They concluded that participants’ conscious awareness of the target shift did not occur until considerable additional processing had been concluded.
The proposal that there may be different processing pathways for conscious perception and motor responses is not new. Milner and Goodale (1992) claimed that these two routes mapped loosely onto two neural pathways, the dorsal and ventral streams, which split having originated in the primary visual cortex. They claimed that the dorsal, or action pathway, projected primarily to the parietal lobes, they termed this the ‘how’ route. Whereas, the ventral, or perceptual pathway, projected primarily to the temporal lobes, they termed this the ‘what’ route. Further to this, similar dissociations between action and perception have since been reported in both neurological patients (Goodale, Milner, Jakobson, & Carey, 1991) and normal populations. The latter in terms of their responses to visual illusions (Aglioti, DeSouza, & Goodale, 1995).

However, the results of Castiello et al’s (1991) experiment have been questioned. Despite Castiello et al’s (1991) use of numerous control conditions Paulignan et al (2000) still proposed possible interactions between the verbal response and motor behaviour. Paulignan et al recently attempted to revisit the question of dissociations between awareness and movement correction. They asked their participants to complete a perturbation trial and then point to where their hand had been when they were aware that the stimulus had moved. Paulignan et al found that their participants had actually begun the correction earlier in their trajectories than the positions they later indicated. They concluded that participants showed delayed awareness of both the target shift and their own correction.
All these studies therefore suggest that early corrections to an ongoing movement can be automated and unconscious. They cannot be adapted and can only partially be suppressed by a participant’s deliberate intention.

However, anecdotal evidence (Day, pers comm) suggests that participants in anti point trials express frustration when they fail to successfully suppress the early incorrect deviation. This would suggest that participants are aware of the early correction even if they cannot suppress it. Day and Lyon (2000) also report that the latency to move in the intended direction in an anti point trial is around 220ms. However, Paulignan et al (2000) report that the awareness gap (the difference between the actual correction latency and the perceived latency) is over 300ms. As such participants should not be aware of their erroneous early correction, as it occurs prior to the point at which they become aware of a target shift.

This raises a number of questions:

- Participants show delayed perceptual awareness of a target shift, but do they show motor awareness of their early corrections?
- Does the level of motor awareness vary if the movement is contrary to an intended action?
- At what latency does the motor correction enter awareness?
- Does an anti point condition, where movement and intention are contradictory, produce a specific conscious experience?
- If so, does a participant’s awareness follow the movement or the intention?
For example, a participant could be asked to over point (move in the same direction as the target shift but go twice as far) rather than anti point (move in the opposite direction to the target shift). It would be expected that participants would initially follow the target, as in an anti point task. However in this case, the early correction would not be contrary to the direction the participants intended to move in. It may be that participants are actually aware of the incongruity between their intended direction and their actual direction, rather than of the early correction per se.

Paulignan et al’s (2000) method of asking participants to subsequently indicate their location at a given event, overcame some of the difficulties of Castiello et al’s (1991) method of verbal report. However, there were still difficulties with it. First, it assumes that participants not only have access to information about their position at discrete points along an ongoing trajectory but that they can explicitly isolate any one of those points at will. Second, it only allows for a single position in the trajectory to be localised.

In the experiment reported here, participants were therefore asked to reproduce the entire path of the movement they had just made rather than simply to indicate a single point. In addition, 3 further conditions were added to the basic pro point (follow the target to its new location) task. These were, anti point (go in the opposite direction to the target shift), over point (go in the same direction as the target shift but go twice as far) and over anti point (go in the opposite direction to the target shift and go twice as far).

This study set out to resolve some of the outstanding questions by:
Comparing participants' actual movements with their movement awareness, rather than with their stimulus awareness.

Considering the effects of a dissociation between intention and movement on awareness.

Considering the potentially qualitatively different experiences of awareness across these conditions.
Method

Participants
14 volunteers were recruited from an opportunity sample of UCL students. They were paid £5 an hour to participate. 2 participants were later excluded. For one, equipment difficulties resulted in an incomplete data set being collected. The other participant did not show the pattern of corrections that this experiment aimed to study. That is, they did not make online corrections when the LED jumped. The unusual combination of fast movement times and slow corrective responses meant the participant reached the central LED then made a second movement to the new location.

Of the remaining participants, 6 were female and 6 were male, all were right handed and had normal or corrected to normal vision by self-report. Their ages ranged from 22-36 years (mean 27.75).

Apparatus
The experiment was conducted in a small, dark testing booth. The experimenter remained present at all times. Participants sat at a desk with their right hand resting comfortably on a response button.

The movement path was tracked using a Polhemus electromagnetic tracker sampling at 120 Hz. The tracker receiver was taped over the nail of the right index finger.

A black vertical mounting board was positioned directly in front of the participant, 40cm from the response button. 5 red LEDs 1cm in diameter were mounted in the
board 3cm above the desk. The central LED was aligned with the response button in the participant's sagittal plane. The other LEDs were aligned horizontally at 10cm intervals, 2 on either side of the central LED. 1 LED at either end of the row was a dummy that never illuminated during the experiment. These were provided to ensure that similar potential target locations, i.e. unilluminated LEDs, were present for the over point conditions as they were for the pro and anti point conditions (see Figure 2.1).

The LEDs were controlled by a computer. This allowed precise synchrony of the LEDs to facilitate a target displacement. The custom-built response key transmitted a signal to the computer when depressed. When the button was released the signal level changed, this could be used to trigger a change in LED illumination.

The LED and response button signals were synchronised with tracker records of the hand position using a software time stamp.
Measurement

Spatial Resampling

On any one trial the initial and reproduced paths could be of different durations. To ensure comparability they were first resampled spatially. That is the X value (lateral deviation) was taken at 1cm values along the Y (reach) axis. These X values were then replotted against Y (distance travelled) rather than against time, this gave a spatial path of the movement.

Estimation Error

The initial and reproduced spatial paths were then compared. Estimation errors were calculated as the difference between the two paths (Figure 2.2).
The reproduced path was subtracted from the initial path at 1cm intervals along the trajectory. The distance between the initial and the reproduced path could then be calculated at each 1cm interval along the reach axis. An example of this is shown in Figure 2.2.

A negative value indicated an under estimation, where the participant was unaware of the extent of their movement or the speed of their correction.

A positive value indicated an over estimation, where the participant was hyper-aware of the deviation in their movement.

The values of the two types of estimation error were then summed. This resulted in two estimation errors for each initial-reproduced path pair.
**Latency Calculations**

On trials when the LED jumped (perturbation trials), the latency of the correction in the initial movement was calculated. However, as the initial and reproduced paths ran over different time courses, an intermediate spatial calculation was required to infer from the reproduced trials the latency at which participants became aware of the correction in the initial movement.

**Figure 2.3 Latency calculation for a median point trial**

![Diagram showing initial and reproduced movement for a median trial in the pro point condition. The initial latency of this trial was 342 ms and the reproduced latency was 505 ms.]

These figures were reached as follows:
First, the simple latency of the initial correction was calculated. The time when the LED jumped was taken as time 0 (A). The correction was defined as having occurred when the subject had moved 2 cm laterally, in the appropriate direction (position 0+2, B). Note that the appropriate direction is towards the target for pointing, but away from the target for anti pointing. The time between the LED jumping (time 0) and this point was taken as the latency of the initial movement (initial latency).

These values were used to estimate latency of awareness using the reproduced movement. The X value used to detect correction in the initial movement (position 0+2, B) was found in the reproduced path (C). Since the reproduced movements did not share a common time course with initial movements, the latency of this point (C) is not interpretable. However, the spatial paths of initial and reproduced movements are related. So, the spatial position of the hand at C can be interpreted. Therefore, the Y value at this point was calculated (D). This Y value was used to relate the reproduced path back to the initial path, and to find its corresponding point in the initial movement (E). The time at this point was then taken as the latency of the reproduced movement (reproduced latency). Note that the reproduced latency is not the time at which the reproduced movement deviated, but the time at which the initial movement had reached the Y position at which participants reproduced a correction.

The difference between the initial and reproduced latencies was defined as the awareness delay, with a positive value indicating that the correction occurred later in the reproduced trial than in the initial trial.
This measure approximately corresponds to that used by Paulignan et al (2000). In that study participants were asked to point to the position at which they had initially begun their correction, here they reproduced the position in their path. This method of movement reproduction was used to calculate the latencies for both point and anti point trials. In addition, it was used to establish whether and when an anti point error (participant corrects towards target instead of away) had been made. As a result, those anti point trials with a detectable anti point error had two latencies: an early error latency when participants moved 2 cm in the wrong direction (towards the target); and a subsequent latency when the subject had reversed the initial error and had moved 2 cm beyond the initial position in the instructed direction (away from the target).

**Design**
The independent variables were pointing task and movement type in a 4 (pro point, anti point, over pro point or over anti point) x 2 (initial or reproduced) repeated measures design. The dependent variables were estimation error measured in cm and response latency recorded in ms.

Trials were presented in blocks. A practice block was completed at the start of each of 4 experimental blocks. The 4 blocked conditions were; pro point, anti point, over pro point and over anti point. The presentation order of the conditions was counter balanced across participants.

Each practice block consisted of 12 trials. In 8 (66%) of the trials the central LED remained on and did not jump, in 2 (17%) it jumped left and in 2 (17%) it jumped right. The data from these practice trials was excluded from all analyses. Each experimental
block consisted of 120 trials. In 80 (66%) trials the central LED remained on and did not jump, in 20 (17%) it jumped left and in 20 (17%) it jumped right. The order of target presentation was randomised using different random orders for each block and for each participant. Each trial consisted of two paired movements, the initial speeded movement and the subsequent unspeeded reproduction of that movement.
**Procedure**

At the start of the testing session, the participant was told that the experiment had two components. The first would be to reach out and touch the central illuminated LED as quickly and accurately as possible before returning to the response button. Then, immediately after completing this task, they were to repeat the path of the movement they had just made, as accurately as possible, but without needing to reproduce the speed precisely.

Participants were then told that on 1/3 of trials the target LED would jump after they had begun to move. The apparatus was demonstrated and participants were shown how the target LED could jump to one side or the other. They were informed that the outside LEDs were dummies and would never illuminate, but that they would be used to indicate target locations in later conditions.

In all conditions, participants were told that if the LED did not jump they should simply continue their movement to the central position and then reproduce their path. For each specific condition they were informed separately of the appropriate response if the LED jumped. These instructions varied according to the blocked condition. The appropriate response for each condition is given below and shown in Figure 2.4.

Pro point, 'if the LED jumps, please follow it to its new location. Please try to correct your movement as quickly and accurately as possible'.

Over pro point, 'please move in the same direction as the LED, but go twice as far. That is, if the LED jumps right, please point to the dummy LED on the far right. Please try to correct your movement as quickly and accurately as possible.'
Anti point, 'please move in the opposite direction to the LED. That is, if the LED jumps right, please point to the unilluminated LED in the equivalent position on the left, and vice versa. Please try to correct your movement as quickly and accurately as possible.'

Over anti point, 'please move in the opposite direction to the LED. That is, if the LED jumps right, please point the dummy LED on the far left of the display, and vice versa. Please try to correct your movement as quickly and accurately as possible.'

**Figure 2.4 Target location and possible movement paths on a perturbation**

At the start of each trial, the central LED would illuminate as soon as the participant placed their finger on the response button. When the participant was ready to begin, they released the button and reached out towards the central LED as quickly and accurately as possible.
In perturbation trials, the release of the start button triggered the LED to jump 25ms later. This was done by switching off the central LED and simultaneously illuminating one of the alternative LEDs. The participant then corrected their movement, according to the condition, in order to reach the target location. They then returned to the start button. The LED remained illuminated at its final location. The participant then reproduced the path of their previous movement as accurately as possible (Figure 2.5).

Figure 2.5 Schematic representation of experimental events across time in a perturbation trial
Results

1: Trial Types and Error Incidence

Median trials for all conditions are shown in Figure 2.6. These figures show the smooth movement of the hand along the Y (reach) axis. The X (lateral deviation) is also plotted. A deviation occurs when the initial position passes the critical initial value + 2cm position. The deviations can be clearly seen within the X path of each perturbed trial. In addition, the early error in the anti point trial can be seen in Figure 2.6g along with an example of a late but appropriate correction in Figure 2.6e.

Central point trials, i.e. those in which the LED did not jump, were not analysed further. Of the remaining perturbation trials 4.2% were discarded overall due to erroneous responses or equipment failure. Specifically, 8.75% of trials were discarded within the anti point condition.

The remaining anti point trials were investigated further. 23% of anti point trials showed a detectable anti point error in both the initial and reproduced path. An anti point error was defined as having occurred if the participant moved 2 cm in the incorrect direction. 59.5% showed no detectable anti point error in either the initial or the reproduced path. 5.8% showed an anti point error in only the initial path and 11.7% showed an anti point error only in the reproduced path.
Figure 2.6 Typical trials from one participant, showing raw paths of initial and reproduced movement pairs for each condition.

<table>
<thead>
<tr>
<th>Initial movement</th>
<th>Reproduced movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center point trial,</td>
<td>a [Y]</td>
</tr>
<tr>
<td>Point trial,</td>
<td>c</td>
</tr>
<tr>
<td>Anti point trial with no error,</td>
<td>e</td>
</tr>
<tr>
<td>Anti point trial with error,</td>
<td>g</td>
</tr>
</tbody>
</table>

100ms
Three major analyses were undertaken.

The simple correction latencies for the initial movements were investigated.

The spatially resampled paths were compared for all conditions.

The initial latencies were revisited and compared to the reproduced latencies.

**2: Simple latencies of initial movements.**

The correction latencies of the initial movements were compared to establish the relationship between the pro point and anti point movements. Trials in the anti point condition were divided into those with detectable anti point errors and those without. Those trials with an anti point error had two latencies. The anti point error latency, (i.e. when the participant had moved 2 cm in the incorrect direction) and the standard latency, (i.e. when the participant had moved 2 cm in the correct direction). The correction latencies are shown in Figure 2.7.

**Figure 2.7 Mean correction latencies in ms (and standard deviations) of initial paths.**

The critical relationships between the latencies were then examined further (Table 2-1).
Table 2-1 Mean correction latencies in ms (and standard deviations) of initial paths

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pro Point</th>
<th>Anti Point Error</th>
<th>Anti Point (no error)</th>
<th>Anti Point (with error)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>354</td>
<td>358</td>
<td>470</td>
<td>761</td>
</tr>
<tr>
<td></td>
<td>(68)</td>
<td>(75)</td>
<td>(152)</td>
<td>(226)</td>
</tr>
</tbody>
</table>

Planned comparisons were conducted as it was predicted that there would be no difference between pro point latencies and anti point error latencies. In addition, it was predicted that latencies in anti point trials that showed no anti point error would differ from both pro point latencies and anti point error latencies.

There was no significant difference between the pro point correction latency and the anti point error latency ($t_{11} = 0.189$, $p = 0.854$). However, the anti point (no error) latency was significantly different from both the pro point latency ($t_{11} = 3.244$, $p = 0.008$) and the anti point error latency ($t_{11} = 2.780$, $p = 0.018$).
3: Spatial Resampling.

The differences between the initial paths and the reproduced paths were then considered. As they were often of different temporal lengths, the data were spatially resampled so that direct comparisons could be made. Only those portions of the spatial paths that were comparable across all trials could be analysed. Differences in starting posture meant that trials differed slightly in their starting position. However, the final position was effectively fixed by the target location for that trial. In all cases at least 27cm of clean data could be identified prior to the target, and this position was used as the starting position for spatial analysis. Paths were plotted backwards after being aligned at the peak Y value, which would be the location of the target LED. This meant that the section lost was at the start of the movement, prior to any corrections, rather than at the end. The averaged spatial paths in each condition are shown in Figure 2.8.
The extent of the estimation errors was calculated by subtracting the X value of the reproduced movement from the X value of the initial movement at 1 cm intervals, (see Figure 2.2 for further details of how the estimation errors were calculated). This resulted in two types of estimation error. The two error types are qualitatively different. An under estimation occurs when the participant is unaware of both speed and the extent of their corrected movement. Over estimation occurs when the participant is hyper-aware of the correction in their movement. In addition, we predict that over
estimations will be present in those trials with an intentional component and that underestimation will be more prevalent in those with an automated response.

By summing the total error this information would be lost. Therefore, in order to investigate fully any difference between motor performance and action awareness, the extent of the over and under estimations were summed separately for each trial. The sum of each type of estimation error was considered for each condition. In addition, the analyses were factoralised in a 2 (point, over point) x 2 (anti, over anti) design, see Figure 2.9 and Figure 2.10.

**Figure 2.9 Sum of under estimation error (cm) for each condition**

There was a significant effect of anti pointing on under estimation error ($F_{1,11} = 11.87$, $p = .005$). Participants were significantly more likely to make under estimations of their motor performance in pro point conditions. There was no significant effect of over pointing ($F_{1,11} = .18$, $p = .68$) and no significant interaction ($F_{1,11} = 1.43$, $p = .26$).
Figure 2.10 Sum of over estimation error (cm) for each condition

In contrast, analysis of the summed over estimation showed that there was an effect of over pointing that approached significance on over estimation error (F_{1,11} = 4.68, p = .053). Participants were more likely to make over estimations in over point conditions.

There was no effect of anti pointing (F_{1,11} = 2.41, p = .15) and no significant interaction (F_{1,11} = 1.48, p = .25).

4: Pro point and anti point initial and reproduced correction latencies.

A striking feature of the spatial paths was the extent of the under estimation error in the basic pro point condition. Reproduced movement paths show that participants are underestimating both the speed and the extent (or gain) of their correction. This can be seen in Figure 2.8 where the initial path consistently remains above the reproduced path. This pattern is not seen in any of the other conditions. The anti point condition shows a smaller, consistent, over estimation of the correction. The over pro point and over anti
point conditions both show some amalgamation of the two, with both under and over estimations along the path. In order to consider these differences more closely the correction latencies of both the initial and reproduced paths were considered.

The initial latencies were calculated as described above (see Table 2-1). The reproduced latencies were calculated by comparing the spatial position (Y: reach axis) of the correction from the reproduced movement with that of the initial movement to give a temporal measure (as described in the method).

This gave a temporal snap shot of the movement at which the correction latency differences could be compared. The over point and anti point conditions could not be considered with this method as they were more complex. For example, the reproduced path could cross the initial path at one or more locations. Therefore, any difference across the conditions latencies would have been too dependent upon the criteria used to have been meaningful. As such, the following analyses were conducted on the pro point and anti point conditions only. Anti point trials were again divided into those with detectable anti point errors and those without. The initial and reproduced correction latencies and the awareness gap (the difference between them) was calculated (Table 2-2).

Examples of median trials were shown in Figure 2.6
Planned comparisons were then conducted on the latencies. It was predicted that the initial latencies would be earlier than the reproduced latencies in the pro point condition. There was a significant difference between the initial and reproduced correction latencies in the pro point condition ($t_{11} = -2.55$, $p = .027$). The correction latency reported in the reproduced path was on average 36ms later than the initial correction. It was also predicted that initial latencies would be later than the reproduced latencies in the anti point condition. There was no significant difference in the anti point error condition ($t_{11} = .60$, $p = .56$), the anti point (no error) condition ($t_{11} = 1.40$, $p = .19$) or the anti point (with error) condition ($t_{11} = .73$, $p = .48$). However, the differences in these conditions do appear to show a trend in the predicted direction (Figure 2.11).
Figure 2.11 Correction latencies (ms) of initial and reproduced paths

The reproduced latencies were 17ms earlier than the initial correction in the anti point error condition, 15ms earlier in the anti point (no error) condition and 61ms earlier in the anti point (with error) condition.

Finally the awareness gap (the difference between the initial latency and the reproduced latency) in the pro point and anti point (no error) conditions was compared (Figure 2.12).

Figure 2.12 Awareness gap
As predicted there was a significant difference between the awareness gap in the pro point and anti point (no error) conditions ($t_{11} = -3.11$, $p = .01$).
Discussion

This experiment confirms that early corrections can be made to an ongoing movement in response to a target shift. However, we found latencies of around 350ms rather than the 150ms or less previously reported (Paulignan et al., 1990; Castiello et al., 1991; Pélisson et al., 1986; Day & Lyon, 2000). This difference is attributable to the strict 2cm-deviation criterion used to calculate latencies in our analyses. Other studies have used less conservative criteria, such as velocity profiles.

Despite using a target jump rather than a constant-velocity shift, the anti point errors and late corrections following their suppression found by Day and Lyon (2000) were also replicated. The latencies of these errors were the same as the latencies of early corrections in pro point trials. No reversal of these erroneous early corrections was seen. In that, early corrections in the appropriate anti point direction were not seen, although they could be suppressed. Latencies in those anti point trials that showed no error were significantly later than for pro point trials.

When the awareness of these corrections was considered the findings initially mirrored those of Castiello et al (1991) and Paulignan et al (2000). That is, participants significantly underestimated their deviation in pro point conditions. This was despite the fundamental difference between Castiello et al’s (1991) study (i.e. they measured stimulus awareness) and this study, (a measure of motor awareness). However, in the anti point condition the opposite pattern was found, with no significant under estimation but an effect of over estimation that bordered on significance. This suggests that
awareness of the movement does differ as a function of the relative involvement of automated and intentional motor mechanisms. Interestingly, the spatial paths of the over pro point condition showed some evidence of under estimation at the start of the movement before crossing to over estimation in the latter part of the trajectory. This suggests an amalgamation of the two systems.

To investigate further, the latencies in the pro point and anti point conditions were considered. Again, our results initially mirrored those of Paulignan et al (2000) in that, participants showed significantly delayed awareness of the deviation in their movement. However, rather than the previously reported awareness gaps of around 300ms (Castiello et al (1991) and Paulignan et al (2000)), we found delays of just 36ms. This would suggest that participants are able to report their corrections more accurately when repeating the whole path than when indicating just one discrete point in the movement. However, despite this additional accuracy the awareness gap was still shown in the expected direction.

However, there was no significant awareness gap in the anti point condition. In addition, the small differences that were shown were all in the opposite direction. Participants believed that they began to deviate earlier than they actually did. This pattern was not only demonstrated in the anti point latencies for movements in the correct direction, but also for anti point errors.

This experiment therefore shows that not only are participants aware of their internal corrections, but that they can also be fully aware of early on-line corrections. However, it would appear that this only happens when the early correction is contrary to the
participant's intention to move in the opposite direction. Unfortunately it was not possible to further analyse the latency data of the over point conditions due to the complexity of the paths. That is, these conditions do not really fit with methods that focus on a specific point of deviation. However, if may be that further investigation of over pointing will provide additional information as to participants’ awareness of an erroneous early correction that is not directly contradictory to their intention.

The simple explanation for these findings would be that the two systems, Frith and Done's (1986) slow and direct routes, cause participants to be differentially aware of their corrections. In anti pointing, the slow, intentional route predominates. This leads to participants not only being aware of their intentional corrections but being more aware of the intention than of the action itself. That is, they believed that they corrected their movement somewhat earlier than they actually did.

The existence of this awareness gap in pro pointing trials is highly consistent with previous research (Castiello et al., 1991). However, the data presented here clearly shows that awareness of behaviourally identical motor events can sometimes occur. In this case the awareness gap is abolished. Castiello et al (1991) claim that this awareness gap, the time difference between when events actually occur and when they are perceived to occur, is caused by the additional processing required before a perturbation enters consciousness. The pattern of data presented here is incompatible with a model that proposes a basic behaviour with awareness following at a fixed latency. Instead, the anti point error data suggests that the cognitive context in which the movement occurs has a major influence on motor awareness.
This experiment has shown that participants can be aware of their early corrections. 
Yet, like Castiello et al (1991) and Paulignan et al (2000) we have also shown that this 
is not always the case. Consequently, current explanations have been shown to be 
insufficient. However, there is not an obvious explanation as to what underlying 
mechanisms could allow an unconscious automated correction to enter awareness. The 
critical feature appears to be whether the early correction matches the intended 
movement. One explanation for this difference is whether a controlling intentional 
supervisory system has been brought into play or not, such as that proposed by Shallice 

When a planned movement is executed, and the overt consequence is the intended goal 
being achieved, the precise details of the movement are subject to an awareness gap. 
However, the automated system responsible for the adaptive corrections can result in a 
consequence that is contrary to intention, following the LED instead of anti pointing. In 
this case, the movement becomes subject to scrutiny by an attentional system that 
inhibits the automated correction allowing the slower controlled anti point. Movements 
controlled by this system become conscious and the participant is able to report their 
deviation. However, sometimes this controlling mechanism is too slow and the 
automated system has already begun the correction. In this situation an anti point error 
occurs. The early correction must then be halted and the direction of the movement 
reversed by the slower controlled system.

We know that the attentional system is not always fast enough to successfully inhibit 
this error on every occasion, it requires a certain amount of time to process and 
implement the new trajectory. However, awareness of the movement may begin from
the time when the supervisory attentional system (SAS) is invoked, rather than from when it begins to correct the movement. Such a SAS had long been argued to both plan intentional movements and monitor automated behaviours (Shallice, 1991). Consequently, even the early on-line correction is available to consciousness, when it constitutes an error.

In conclusion, we have demonstrated that participants' awareness of their early on-line corrections is normally delayed relative to their performance. Therefore, in the basic case at least, Castiello et al (1991) were correct. However, awareness of a correction is dependent upon its relationship to the intentions of the participant. It is proposed that the invoking of an over riding supervisory attentional system (Shallice, 1991) is the cause of this difference.

A number of important questions remain:

What is the role of intention in awareness?

How does motor awareness relate to perceptual awareness of the target shift?

Can a participant ever be fully aware of an appropriate early on-line correction?

What is the neural basis of the mechanism that underlies awareness?

We hope to begin to answer these questions in the following chapters.
3. Experiment 2: Awareness of online motor corrections in the absence of perceptual awareness

Introduction

Experiment 1 confirmed previous findings that participants are able to make fast online correction to target shifts (Day & Lyon, 2000; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991a; Pélisson et al., 1986). It also confirmed that participants are only able to do this when the correction is directly mapped to the stimulus. When they are required to make an anti point in response to a target shift, early corrections are suppressed and a later response is seen. Where an early response is present in this condition, it is in the erroneous direction (Day & Lyon, 2000).

Experiment 1 also demonstrated the novel finding that participants are able to report their awareness of their movements through movement reproduction. Movement reproduction was found to be an appropriate, intuitive and sensitive measure of motor awareness. It was found that participants significantly under estimate the speed and extent of their awareness when pro pointing, but not when anti pointing. This suggests that intention may play a critical role in the attenuation of awareness.
Previous research has demonstrated that motor performance can dissociate from perceptual awareness. Pélisson et al (1986) asked participants to look and reach to a target that would sometimes move during their saccade. Under these conditions the target shift is subject to saccadic suppression, and so the participant remains unaware of its movement. However, Pélisson et al (1986) found that participants were equally efficient at pointing to the final target location as when there had been no target shift. The authors concluded that these corrections occurred without entering consciousness.

The correction in this case is probably not volitional in the sense that it is not freely willed, but a direct response to the stimulus. However, even within these automated stimulus driven actions, there is still an intentional component. The intention here is to reach the target, this requires an implicit intention to follow the target if it moves, regardless of whether the participant is aware of the movement. If the target shifts and the participant does not correct their movement they will fail to reach it and so will record it as an error.

These automated corrections in the absence of awareness of the cause also have parallels within the neuropsychological literature; notably, anarchic hand syndrome. Typically an anarchic hand patient will present claiming that some or all of the time they have no control over a limb, usually the left hand of a right-handed patient (Ay et al., 1998). Although some loss of motor control following a neurological problem is not particularly unusual, anarchic hand patients differ in that they fail to recognise the action of the hand as ‘theirs’ (Ay et al., 1998). That is, they do not recognise the movement was self initiated and instead categorise their limb’s behaviour as ‘other’.
This can result in claims that the limb itself has intent, independent of the intentions of its owner. In addition, the intent is often perceived as malevolent (Persaud, 1999).

Of course, in saccadic suppression tasks, participants do not confabulate malevolent intent to their arm. However, they do appear to be unaware of the cause of the change in their movement. Indeed, they appear to be unaware of the behavioural change itself (Péligson et al., 1986; Desmurget et al., 1999). In Experiment 1 when participants made unintended, erroneous corrections in the anti point conditions they were observed to frequently express frustration and annoyance that they had made a mistake (also Day, pers comm.). In that situation they were clearly aware that they had made an unintended movement. Compare this with Péligson et al’s (1986) task where they appear to be unaware of the movement which achieved an intended goal.

This again raises the question of the role of intention in attenuating awareness.

However, a major criticism of Péligson et al’s (1986) experiment is that motor awareness was not measured directly. Although participants were asked generally whether they were aware of anything 'unusual' about their movements, it was not investigated methodically. Instead, it is assumed to be lacking because there is no awareness of the stimulus shift. Besides parsimony, there is no immediately obvious reason to assume that motor awareness is equal to stimulus awareness. Péligson et al (1986) have shown that motor performance can dissociate from perceptual awareness. Experiment 1 demonstrates that motor awareness can dissociate from motor performance. Therefore it is reasonable to ask the question, can motor awareness dissociate from stimulus awareness?
In Pélisson et al's (1986) experiment participants make an efficient online motor correction in the absence of awareness of the target shift. What then, happens to motor awareness under these circumstances? The potential relationships between perceptual and motor awareness are shown in Figure 3.1.

Figure 3.1 Schematic showing potential relationships between perceptual and motor awareness

<table>
<thead>
<tr>
<th>Perceptual Awareness</th>
<th>Motor Awareness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aware</td>
<td>Aware</td>
</tr>
<tr>
<td></td>
<td>Unaware</td>
</tr>
<tr>
<td>Unaware</td>
<td>Y/N Participant's awareness of target shift</td>
</tr>
<tr>
<td>Reproduced trajectory</td>
<td>Target shift</td>
</tr>
</tbody>
</table>

-75-
Previous research suggests that participants are able to correct their movement regardless of whether they are aware of the target shift (Pélisson et al., 1986). If they are aware of their correction, but unaware of the target shift Pattern A would be found. Pattern B would indicate that they were unaware of both their correction and the target shift. Pattern C would indicate that the participant was aware of both their correction and the target shift, whilst pattern D would show that they were aware of the target shift, but not of their correction. Either Pattern A or Pattern D would demonstrate a dissociation between perceptual and motor awareness.

In this experiment, participants were therefore again asked to reach out to a target and to then reproduce the entire path of the movement they had just made. On some trials the target would unexpectedly jump. A subset of the jump trials would be susceptible to saccadic suppression, and so the participant should remain unaware of the target shift.

This study aimed to resolve the question:

When motor performance and stimulus awareness dissociate, what happens to motor awareness?
Method

Participants
16 volunteers were recruited from an opportunity sample of UCL students. They were paid £5 an hour to participate. One participant was later excluded as they made too many false positives and errors on the jump identification (17%).

Of the remaining participants, 10 were female and 5 were male, all were right handed and had normal or corrected to normal vision by self-report. Their ages ranged from 20-35 years (mean 25.93).

Apparatus
The experiment was conducted in a small, dark testing booth. The experimenter remained present at all times. Participants sat at a desk with their head on a chin rest. Their right hand rested comfortably on the edge of the desk, with their elbow to the side of their body. A semi-silvered mirror occluded the hand at all times.

The movement path was tracked using a Polhemus electromagnetic tracker sampling at 120 Hz. The magnet block was taped over the nail of the right index finger. As the coordinates recorded are those of the magnet block and not the actual finger tip, all measurements are subject to a small error that is constant for each participant.

All targets were 7mm in diameter and were projected onto the workspace directly in front of the participant. The central target was aligned with their finger. The other targets were aligned horizontally at 8cm intervals, 1 on either side of the central target.
When the central target ‘jumped’ it moved 4cm horizontally in either direction (see Figure 3.2). The fixation point was 11mm in diameter and was 40cm to the left of the central target, and also aligned horizontally with it. The guideline for the reproduced movement was a single line, 2mm thick, across the full width of the display, at the same horizontal position as the fixation point and all targets. The end of both initial and reproduced movements was defined as the point at which the velocity of the finger fell below 5cm/sec.

**Figure 3.2 Experimental set-up**

The display, including the fixation point, all targets and the guideline, was generated and controlled by a computer using a custom programme. This allowed close synchrony of the targets to facilitate the illusion of the jump.
**Design**

The independent variables were side, awareness and movement type in a 2 (left or right) x 2 (aware or unaware) x 2 (initial or reproduced) repeated measures design. The dependent variable was horizontal end point, recorded in mm from the center position. A minus figure indicates a leftward deviation, positive indicates rightward.

Trials were presented in blocks. A practice block of 10 trials was completed first, followed by 240 experimental trials in blocks of 20. In 60 trials, the central target illuminated; in 50 trials, the left target illuminated; and in 50 trials, the right target illuminated. In a further 40 trials, the center target appeared and then jumped left; and in 40 trials, it jumped right. Trial order was randomised across participants. Each trial consisted of one initial movement - reproduced movement pair.

The left and right target trials were used so that participants could not simply use a variation from the center to extrapolate that the target had shifted. They will not be included in the analyses.

The verbal report of the target jump was always given after the movement was reproduced. It was decided not to counter balance this for a number of reasons. First, it was thought possible that motor awareness may decay rapidly. Second, previous researchers have believed that it is sufficient to ask the question at the conclusion of the entire experiment (Pélisson et al., 1986; Desmurget et al., 1999). Therefore, to ask at the end of each the trial already provides additional detail. Finally, it has long been known that vision can dominate proprioception, especially when the two senses provide
contradictory information (Rock & Yeshiva, 1967). It was therefore a concern that visual information about the target might over ride any motor awareness of a correction.

**Procedure**

Participants were told that the experiment had three components. The first would be to reach out and touch the illuminated target as quickly and accurately as possible before returning to the start position. Then, immediately after completing this task, they were to repeat the path of the movement they had just made, as accurately as possible. Finally, they were to indicate whether or not the target had jumped with a verbal response, either ‘left’, ‘right’ or ‘no’.

Participants were instructed that on some of the trials, the target would jump after they had begun to move. The apparatus was demonstrated and participants were shown how the central target could jump to one side or the other.

In all conditions, participants were told that if the target did not jump they should simply continue their movement to the original position and then repeat their path and report ‘no’. If it did jump, they were to follow it to its new location as quickly and accurately as possible, and then to report the direction of the jump.

Each trial began with a starting point illuminating at the edge of the desk to the right of the participant. As soon as the participant placed their finger here, the fixation point would illuminate for between 2000-3000 ms. The fixation point was then extinguished and a target immediately appeared. On jump trials, the central target was extinguished 200-300 ms after target onset and immediately reappeared at its new location. As soon
as the fixation point was extinguished, participants looked at, and reached to, the target as quickly and accurately as possible. At the end of the movement, the target was extinguished and participants returned to the starting position. The guideline then appeared and participants repeated their previous movement path. At the end of the reproduced movement, the guideline disappeared and participants again returned to the starting point. They then gave their verbal report of the target jump. The experimenter recorded their response on the computer and this triggered the start of the next trial (see Figure 3.3).

Figure 3.3 Schematic representation of experimental events across time in a perturbation trial.
Results

Target Jump Awareness

For each participant there were a total of 80 jump trials; 40 in each direction. These were divided into those in which the participant was aware of the target jump and those in which they were not. 34% (21.5 SD across participants) of leftward jumps were categorised as ‘aware’ and 62% (20.8) as ‘unaware’. For rightward jumps 39% (26.1) were categorised as ‘aware’ and 55% (25.7) as ‘unaware’. The remaining jump trials were rejected as errors.

Error Incidence

84% of trials were included in the final analyses. 6.34% of trials were omitted due to equipment failure. 2.11% of trials were omitted due to pre-emptive eye or hand movements. 7.8% of trials were omitted as false positives (reporting a jump in non-jump trials) or wrong direction (in jump trials).

End Points of Initial Movements.

It was found that the movements were subject to a rightward bias in all conditions. This was greater in the initial movements than the reproduced movements. As such it was not possible to conduct a trajectory analysis on the data, as any effect of awareness would have been subsumed in the difference caused by the rightward bias. Therefore, the calculations were conducted on the endpoints instead.

Endpoints of all jump trials can be seen in Table 3-1.
Table 3-1 Mean endpoints of initial movements in mm from center (and standard deviations)

<table>
<thead>
<tr>
<th>Endpoint</th>
<th>Left Aware</th>
<th>Left Unaware</th>
<th>Center</th>
<th>Right Aware</th>
<th>Right Unaware</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-9</td>
<td>-11</td>
<td>25</td>
<td>57</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>(29)</td>
<td>(30)</td>
<td>(30)</td>
<td>(36)</td>
<td>(34)</td>
</tr>
</tbody>
</table>

Note: A negative value indicates a leftward deviation. A positive value indicates a rightward deviation. As there is no jump to be aware of in Center trials there is no aware/unaware distinction in that condition.

The endpoints of the initial paths were considered first. Trials in which the target jumped were divided into those in which the participant detected the jump (aware) and those in which they did not (unaware). To establish whether online corrections had been made, the endpoints were compared with those trials in which the target remained in the center and did not jump. A significance level of less than .008 was required following family wise Bonferroni corrections. All differed significantly from the center point trials regardless of whether the participant was aware (left: $t_{14} = 11.43$, $p > .001$, right: $t_{14} = -8.07$, $p > .001$) or unaware (left: $t_{14} = 16.75$, $p > .001$, right: $t_{14} = -21.41$, $p > .001$) of the target shift. The effect of perceptual awareness on the extent of these corrections was then considered. No significant difference was found between the endpoints of aware and unaware trials for jumps to either the left ($t_{14} = 1.54$, $p = .15$) or the right ($t_{14} = -.58$, $p = .57$). That is, participants were just as efficient in correcting to the target shift regardless of whether they were aware of the jump.
End Points of Initial and Reproduced Movements.

Typical trials for one participant are shown in Figure 3.4.

Figure 3.4 Typical trials for one participant showing trajectories for initial and reproduced movements
The relationship between the initial endpoints and those of the reproduced movements in the jump trials was then considered (see Table 3-2).

<table>
<thead>
<tr>
<th>Movement</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aware</td>
<td>Unaware</td>
<td>Aware</td>
</tr>
<tr>
<td>Initial</td>
<td>-9</td>
<td>-11</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>(29)</td>
<td>(30)</td>
<td>(30)</td>
</tr>
<tr>
<td>Reproduced</td>
<td>-28</td>
<td>-32</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>(32)</td>
<td>(29)</td>
<td>(29)</td>
</tr>
</tbody>
</table>

A 2x2x2 ANOVA was conducted on the data see (Figure 3.5). The factors were side (left, right), awareness (aware, unaware) and movement (initial, reproduced). As expected, a significant effect of side was found ($F_{1,14} = 265.96, p > .001$). The average endpoints to targets that jumped to the left were 20mm to the left of center. Average endpoints to targets that jumped to the right were 58.8mm to the right of center. There was no significant effect of awareness ($F_{1,14} = .35, p = .56$).
There was a significant effect of movement ($F_{1,14} = 22.49$, $p > .001$). The mean endpoint of initial movements was 25mm; for reproduced movements, it was 13mm. That is, initial movements showed a general rightward bias of 12mm. A significant interaction between side and movement ($F_{1,14} = 24.1$, $p > .001$) indicated that this effect differed according to side. Initial endpoints to rightward targets were 4mm to the right of reproduced endpoints. Initial endpoints to leftward targets were 20mm to the right of reproduced endpoints.

Critically, there was no significant interaction between movement and awareness ($F_{1,14} = 2.92$, $p = .11$), nor awareness and side ($F_{1,14} = 1.91$, $p = .19$). That is, movement reproduction did not differ between those trials in which the participants were perceptually aware and when they were unaware. It could be argued that there is a trend towards an interaction between movement and awareness, however, this is driven by a
slight tendency to make a greater correction to the right when unaware of a target shift, but to reproduce a greater correction to the left. In both initial and reproduced movements greater corrections were always slightly further for targets that participants reported had not jumped, than for those that did. Therefore, even if that trend were significant it would not contradict the main results here. Finally, there was no interaction between side, awareness and movement ($F_{1,14} = .015$, $p = .91$).
Discussion

End Points of Initial Movements

The mean end point of the movements during which the target jumped significantly differed from the mean end point of the central trials. No significant difference was found between the endpoints for those trials in which the participant was aware of the target shift and those in which they were not. This confirms previous findings that efficient corrections can be made to an ongoing movement in response to a target shift regardless of whether the participant is aware of that target shift (Desmurget et al., 1999; Pélisson et al., 1986; Day & Lyon, 2000; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991b).

All the initial movements in all conditions were subject to a rightward bias. That is, in all conditions the participants pointed approximately 2 cm to the right of the actual target location. This was compatible with existing literature where bias and variability have previously been found to occur within the plane of a movement (Haggard & Richardson, 1996). The bias seen in this experiment was probably due to a number of factors including:

- All participants were right handed and using their dominant hand for the task
- The experiment was conducted in the dark
- The hand was occluded at all times
- The head was in a fixed position
Although the bias was unfortunate and unexpected, it was constant and so did not affect the overall finding; that participants made online corrections to the target shifts regardless of awareness.

**End Points of Initial and Reproduced Movements**

The end points of participants reproduced movements did not differ significantly according to whether they were aware of the target shift. This demonstrates the novel finding that motor awareness can dissociate from perceptual awareness. That is, even when they believe that the target did not shift, participants still report the deviation in their movement. They are able to report their motor awareness of their movement despite having no conscious knowledge of the stimulus event that drove it.

The end points of the reproduced movements were significantly different from the initial movements. Specifically, the reproduced movements were less susceptible to the rightward bias. Unfortunately, a directional bias that differed according to movement type meant that a direct comparison of the entire spatial paths was not viable. The bias seen was 50% of the size of the target shift. It would not be possible to conclude that any under or over estimation of the paths was due to attenuated awareness of the motor correction, rather than simply a lack of awareness of the constant bias. It would be of interest to attempt to replicate this study under a variety of experimental conditions with a view to reducing the constant bias and allowing such a comparison to be made.
Conclusions

It would seem that when reproducing a movement participants are not simply re-running the previously used motor programme. If this were occurring then the rightward bias should be equally present in both the initial and reproduced movements. Nor are they simply pointing to the target’s final location, as the reproduced end points show considerable deviation from the actual target locations. This would suggest that participants are genuinely reporting their motor awareness as this is the movement they believe they made, rather than the one they actually made, or the one they should have made. In addition, it would seem that this report of motor awareness takes a form from which information cannot always be extrapolated. That is, participants were not able to utilise information about their trajectory deviation to infer a target shift, even when they were explicitly trying to identify such shifts. This suggests that motor awareness can be encapsulated, and not always available to global consciousness.

It was previously suggested that intention may play a major role in awareness. Here, the participants are unaware of any intention to correct their movement when they are unaware of the target shift, although they are presumably aware of their intention to reach the target. However, they do appear to have some awareness of the motor correction, but this appears to be attenuated and unavailable to higher processing that would allow participants to make inferences about the cause. Instead motor awareness appears to be encapsulated within the motor system. It may be that there are multiple forms of awareness (perceptual, motor, etc) that enter global consciousness independently. This would be compatible with ideas of an over riding form of consciousness that acts as a Global Workspace, collating and redistributing information.
throughout the brain (Baars, 1983). Perhaps then, the role of intention is to determine which of the data from the minor systems is transferred on to the global system.

It is of interest to note that this lower form of awareness, a report of a motor correction that does not appear to be fully conscious, or at least cannot be used to infer a target shift, occurs on an appropriate, highly automated movement. That is, an online motor correction that allows the participant to successfully complete the intended task. Compare this with the findings from Experiment 1, where participants were able to report early, automated corrections, but only when those corrections were erroneous pro points in the intentional anti point condition. It may therefore be that this is a demonstration of a continuum of awareness, much like the continuum of automated behaviour proposed by Day and Lyon (2000).
4. Experiment 3: Disrupting motor corrections and motor awareness with TMS

Introduction

Experiment 2 demonstrated that participants can show motor awareness of an online correction, even when they are unaware of the stimulus shift that caused it. However, it also raised questions about what motor awareness is actually an awareness of. It was not simply a re-running of the previously used motor plan, nor were they just reporting the target location. They therefore appear to be reporting a movement that they believed they had made. Where then would such an awareness arise within the processing stream?

One way to address this question is to disrupt the processing stream and see what effect this has on the participant's motor awareness. Desmurget et al (1999), prevented online motor corrections to covert target shifts through the use of TMS. They used the saccadic suppression paradigm of Pélisson et al (1986) that was also used here in Experiment 2. In addition, they delivered a single pulse of trans-cranial magnetic stimulation (TMS) to the posterior parietal cortex at movement onset. They reported that trajectory corrections were suppressed in the majority of their participants.

If these participants were asked to reproduce the movement that they made, what pattern would their movements show? Are they aware that the TMS pulses interfere with their
movements? If motor awareness arises prior to the neural locus at which the TMS pulse suppresses the online correction then participants may still reproduce a curved trajectory. In this case the participant would neither have intended to correct their trajectory, nor physically corrected it. They would be reproducing a movement that they did not make, with no awareness of the stimulus shift that caused it. Alternatively, failing to correct the movement would effectively cause participants to make an error as they would not reach the target. Experiment 1 suggests that erroneous movements may be subject to a privileged form of awareness, suggesting that this possibility deserves further investigation. More generally, the TMS disruption paradigm of Desmurget et al (1999) seems a valuable tool for dissociating motor awareness from both motor performance and perceptual awareness.

In order to consider these questions more thoroughly it may be helpful to consider a possible model that shows ways in which the various factors could interact (see Figure 4.1). This model provides a useful framework within which the various possibilities can be considered.

The role of visual perception within this model will not be a primary concern here. The important feature for this model is that this information feeds directly into the motor system for use in visually guided movements. This may occur through connections from the visual system to the Posterior Parietal Cortex (PPC). In addition, it is suggested that there is some higher mental representation of the task. This would include what the participant intended to do and perhaps an action plan to achieve it. Possible neural areas that may be implicated in such a representation would be the pre motor cortex (PM) and associated Basal Ganglia (BG) regions that form an intricately connected cortical-sub
cortical-cortical circuit (Alexander, DeLong, & Strick, 1986). This circuit is believed to be involved in visuomotor processing. It has previously been argued that PM is implicated in vision-for-action routes in primates (Boussaoud, di Pellegrino, & Wise, 1996). The PM has also been specifically identified as being involved in the planning and execution of intentional movements in primates (Boussaoud, 2001).

Figure 4.1 A model of representations and processes involved in visuomotor actions and their relations to motor awareness.

Boussaoud et al (2001) attempted to subdivide this area further in both primates and humans. Specifically, they found that in humans intentional tasks activated anatomically close but distinct areas within the PM when compared with attentional tasks. These studies suggest that the PM plays a role not only in planning and executing intentional movements, but may also eventually explain the link between intention and attention.
The Posterior Parietal Cortex (PPC) is believed to be involved in sensorimotor integration (Wolpert, Goodbody, & Husain, 1998). It has also been claimed that it has a major role in on-line control of visually guided movements (Pisella et al., 2000). Neurological data suggests that patients with lesions in the PPC are unable to make fast online corrections (Gréa et al., 2002). However, other researchers have claimed that it is also involved in awareness of intentional movements (MacDonald & Paus, 2003).

MacDonald and Paus (2003) used rTMS to disrupt this area and found that participants were impaired at judging whether an observed movement was in synchrony with their own. MacDonald and Paus (2003) argued that a comparison of visual and efference copies are used to help generate feelings of agency.

Desmurget et al (1999) have also argued that the PPC is involved in comparing expected with actual outcomes. They used TMS to disrupt the PPC and found that automated corrections were suppressed. They argued that this was further evidence that the PPC is involved in internal representations that are used to determine motor error in real time. In a further experiment (Desmurget et al., 2001) the PPC was also implicated in network that also included the cerebellum and primary motor cortex. This PET study showed that the above areas appeared to be specifically involved in the online corrections during these reaching tasks. This view would be consistent with those of both Pisella et al (2000) and Wolpert et al (1998). It is also consistent with neurological data that shows similar disruptions to these movements following lesions in the PPC (Gréa et al., 2002) and also those that suggest that sub-cortical pathways play a role in these reaching movements (Day & Brown, 2001).
Within the model presented in Figure 4.1 the left hand PPC stream would correct precise movement error through fast online corrections. The right hand motor awareness stream would collate information on goal error, and mediate slow, intentional corrections. It would also allow an accurate reconstruction of the action after the event. Although links to motor awareness are proposed in Figure 4.1 it is not yet known exactly where or how it fits into this system. However, Experiment 2 suggests that motor awareness is at least partly independent of both perceptual awareness and motor performance. Experiment 1 indicates that intention and error detection may play major roles. It is therefore proposed that awareness is occurring in a parallel pathway fed by representations of both internal predictive and external error feedback loops. If this proposal is correct, then disrupting the processing of error feedback could also have an effect on motor awareness.

If awareness is driven by both the internal representation of intention, and also by an error correction feedback loop, then disruption of the PPC would leave participants with only the former on which to base their motor awareness. Alternatively, it may be that the error feedback loop remains intact, but the PPC is unable to implement its corrections. In which case participants may believe they made the correction, even when it was actually suppressed. Asking participants to reproduce movements they made in which they failed to make an appropriate correction, may give us an insight into the neural stage at which motor awareness arises.

The experiment reported here is heavily based on that of Desmurget et al (1999). Therefore, their methods are now described in detail. As mentioned previously, Desmurget et al (1999) combined single pulse TMS and a saccadic suppression task.
They used a semi silvered mirror and an array of LEDs in a set up similar to that used in Experiment 2. The target shift was performed by turning off one LED and illuminating one 7.5° to the side of it. This shift occurred at the peak velocity of the saccade on 1/3 of trials. They report that participants were unaware of both the target shifts and of any motor interference from the TMS pulses.

Desmurget et al (1999) administered a TMS pulse as soon as the participant began to move. The pulse was delivered with a custom iron core coil at 120% of the motor threshold. The stimulation site they aimed for was the intraparietal sulcus of the PPC. This was identified by finding the motor area for the hand then moving the coil 4.5cm caudal and .5cm medial. The coil was held at an oblique angle. Temporal control sites were also used, and EMG recordings were taken to rule out muscle twitches, etc of the limb as the cause of any effect.

Five participants were tested with 10 repetitions each. In the experimental condition they found that two participants showed only slight corrections towards the very end of their movements. Two showed no corrections at all, and the fifth was unaffected by the TMS pulse. For those participants affected by the TMS, it was also seen to influence the mean error magnitude, which increased for three participants and reduced for the fourth. Endpoint variability was also found to be greater following TMS stimulus. Further analyses showed no other difference between jump and no jump trials, or TMS and no TMS trials. This included factors such as movement duration, mean velocity, etc.

Desmurget et al (1999) also conducted a control condition with the non-dominant hand to rule out a visual basis for the effect. They found TMS to the left PPC had no
significant effect when reaching with the left hand, although one participant did show a change in endpoint accuracy.

Following the experiment Desmurget et al (1999) performed a magnetic resonance imaging (MRI) scan on the participants. They were then able to confirm that the location they had been stimulating was indeed appropriate to stimulate the intraparietal sulcus and surrounding areas. Desmurget et al (1999) concluded that the TMS pulse was either preventing computation of the motor error, or disrupting the pathways along which the necessary information travels.

Experiment 3 will combine the TMS paradigm of Desmurget et al (1999) with the movement reproduction task used in Experiment 2. By comparing the pattern of participants reproduced movements with those seen in Experiment 2 it may be possible to draw conclusions about the stage at which motor awareness arises and the neural events that drive it.
Method

Participants
7 volunteers were recruited from an opportunity sample of UCL students. They were paid £7.50 an hour to participate. Two participants were later excluded. One was excluded due to equipment failure, and one was excluded due to too many false positives and errors on the target jump identification (21%) suggesting anomalous perceptual awareness.

Of the remaining participants, 4 were female and 1 was male, all were right handed and had normal or corrected to normal vision by self-report. Their ages ranged from 21-31 years (mean 25.6).

Apparatus
The experiment was conducted in a small, dark testing booth. The experimenter remained present at all times. Participants sat at a desk with their head on a chin rest. Their right hand rested comfortably on the edge of the desk, with their elbow to the side of their body. A semi-silvered mirror occluded the hand at all times.

All targets were 7mm in diameter and were projected onto the workspace directly in front of the participant. The central target was aligned with their finger. The other targets were aligned horizontally at 8cm intervals, 1 on either side of the central target. When the central target ‘jumped’ it moved 4cm horizontally in either direction (see Figure 3.2 in the previous chapter). The fixation point was 11mm in diameter and was
40cm to the left of the central target, and also aligned horizontally with it. The guideline for the reproduced movement was a single line, 2mm thick, across the full width of the display, at the same horizontal position as the fixation point and all targets. The start of the initial movement was determined as being when the velocity of the finger reached 5cm/sec. The end of both initial and reproduced movements was defined as the point at which the velocity of the finger fell below 5cm/sec.

The movement path was tracked using a Polhemus electromagnetic tracker sampling at 120 Hz. The tracker block was taped over the nail of the right index finger.

Transcranial magnetic stimulation (TMS) was delivered using a Magstim 220 with a double (figure of eight) 70mm coil. All other aspects of TMS were the same as those used by Desmurget et al (1999). A single pulse was administered, the intensity was set to 120% of the participant's motor threshold. The coil was positioned over the PPC; 4.5 cm caudal and 0.5 cm medial from the hand motor cortex.

Eye movements were monitored by recording EOG. Disposable Ag/AgCl surface electrodes (ARBO Inc) were used. They were positioned on either temple. The signals were monitored online by a computer. In jump trials the target moved 25-100ms after the saccade onset.

The display, including the fixation point, all targets and the guideline, was generated and controlled by a computer using a custom programme. This allowed close synchrony of the targets to eye movements to facilitate the illusion of the jump. In
addition, the programme also controlled the TMS impulse. This was administered as soon as the initial movement began on 50% of all trials.

**Design**
The independent variables were TMS (TMS or no TMS), awareness (aware or unaware) and movement (initial or reproduced) in repeated measures design. The dependent variable was horizontal end point, recorded in mm from the center position. A positive value indicates a leftward deviation. A negative value indicates a rightward deviation.

Trials were presented in blocks. A practice block of 10 trials was completed first, followed by 240 experimental trials in blocks of 20. In 60 trials, the central target illuminated; in 50 trials, the left target illuminated; and in 50 trials, the right target illuminated. In a further 40 trials, the center target appeared and then jumped left; and in 40 trials, it jumped right. In half of each trial type a TMS pulse was delivered a soon as the participant began their reaching movement. Trial order was randomised across participants. Each trial consisted of one initial movement - reproduced movement pair.

**Procedure**
Participants were told that the experiment had three components. The first would be to reach out and touch the illuminated target as quickly and accurately as possible before returning to the start position. Then, immediately after completing this task, they were to repeat the path of the movement they had just made, as accurately as possible. Finally, they were to indicate whether or not the target had jumped with a verbal response, either ‘left’, ‘right’ or ‘no’.
Participants were instructed that on some of the trials, the target would jump after they had begun to move. They were also told that on half of all trials they would receive a TMS pulse. The apparatus was demonstrated and participants were shown how the central target could jump to one side or the other.

In all conditions, participants were told that if the target did not jump they should simply continue their movement to the target, then reproduce their path and report ‘no’. If it did jump, they were to follow it to its new location as quickly and accurately as possible, reproduce their path and then report the direction of the jump.

Each trial began with a starting point illuminating at the edge of the desk to the right of the participant. As soon as the participant placed their finger here, the fixation point would illuminate for between 2000-3000 ms. The fixation point was then extinguished and a target immediately appeared. On jump trials, the central target was extinguished 25-100 ms after saccade onset and immediately reappeared at its new location. As soon as the fixation point was extinguished, participants looked at, and reached to, the target as quickly and accurately as possible. On TMS trials the pulse was delivered as soon as the initial movement began.

At the end of the movement, the target was extinguished and participants returned to the starting position. The guideline then appeared and participants reproduced their previous movement path. At the end of the reproduced movement, the guideline disappeared and participants again returned to the starting point. They then gave their verbal report of the target jump. The experimenter recorded their response on the computer and this triggered the start of the next trial (see Figure 4.2).
Figure 4.2 Schematic representation of experimental events across time in a perturbation trial.

- Participant gives verbal report of target jump, 'No', 'Left' or 'Right'
- Participant immediately reproduces movement
- Guideline appears
- Participant returns to start
- Participant reaches target, target off
- (If perturbation trial) target jumps 4 cm left or right 25-100 ms after saccade onset
- (If TMS trial) pulse is administered at movement onset
- Participant saccades and reaches towards target
- Fixation point off, target on
- Fixation point on for 2000-3000 ms
Results

Target Jump Awareness

For each participant there were a total of 80 jump trials; 20 with TMS in each direction, and 20 without. These were divided further into those in which the participant was aware of the target jump and those in which they were not. For the TMS trials 49% (25.1 SD across participants) of leftward jumps were categorised as 'aware' and 48% (25.2) as 'unaware'. For rightward jumps 44% (19.2) were categorised as 'aware' and 53% (17.5) as 'unaware'. For the no TMS trials 48% (21.1 SD across participants) of leftward jumps were categorised as 'aware' and 45% (21.5) as 'unaware'. For rightward jumps 56% (16.4) were categorised as 'aware' and 32% (13.0) as 'unaware'. The remaining jump trials were rejected as errors.

Error Incidence

78.45% of trials were included in the final analyses. 10.62% of trials were omitted due to equipment failure. 2.68% of trials were omitted due to pre-emptive eye or hand movements. 8.2% of trials were omitted as false positives (in non-jump trials) or wrong direction (in jump trials).

End Points of Initial and Reproduced Movements without TMS.

As in Experiment 2, the movements were subject to rightward bias, therefore analysis focuses on the lateral (X) deviation of movement endpoints. Mean Endpoints of jump trials without TMS can be seen in Table 4-1.
Table 4-1 Mean endpoints of initial and reproduced movements in mm from center
(and standard deviations) in no TMS conditions

<table>
<thead>
<tr>
<th>Movement</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aware</td>
<td>Unaware</td>
<td>Aware</td>
</tr>
<tr>
<td>Initial</td>
<td>-15</td>
<td>-17</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>(44)</td>
<td>(44)</td>
<td>(35)</td>
</tr>
<tr>
<td>Reproduced</td>
<td>-30</td>
<td>-28</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>(29)</td>
<td>(36)</td>
<td>(38)</td>
</tr>
</tbody>
</table>

Note: A negative value indicates a leftward deviation. A positive value indicates a rightward deviation. As there is no jump to be aware of in Center trials there is no aware/unaware distinction in that condition.

To establish whether online corrections had been made in the initial movements, the endpoints of jump trials were compared with those trials in which the target remained in the center and did not jump (see Figure 4.3). First the jump trials in which no TMS was administered were compared with the equivalent center point condition. (A family wise Bonferroni correction was performed, and so the significance level for the following t-tests is .0125). All differed significantly from the center point trials regardless of whether the participant was aware (left: $t_4 = 10.85$, $p > .001$, right: $t_4 = -8.69$, $p > .001$) or unaware (left: $t_4 = 8.30$, $p > .001$, right: $t_4 = -7.19$, $p = .002$) of the target shift.

The effect of awareness on the extent of these corrections was then considered. (A family wise Bonferroni correction was performed, and so the significance level for the following t-tests is .025). No significant difference was found between the endpoints of aware and unaware trials for jumps to either the left ($t_4 = .77$, $p = .49$) or the right ($t_4 = -.14$, $p = .89$). That is, in trials in which no TMS was administered, participants were just as efficient in correcting to targets regardless of whether they were aware of the jump.
The effect of awareness of the target jump on motor awareness was then considered by comparing the endpoints of the reproduced movements. The endpoints of the non TMS target jump trials in which participants reported perceptual awareness of the target jump were compared with their equivalent counterpart when they reported that there was no jump. (A family wise Bonferroni correction was performed, and so the significance level for the following t-tests is .025). No significant differences were found (left: \( t_{4} = .39, p = .71 \), right: \( t_{4} = .45, p = .68 \)). Therefore, as seen in the previous experiment, participants are equally efficient at reproducing the correction of their trajectory regardless of whether they are aware of the stimulus shift that caused it.

**End Points of Initial and Reproduced Movements with TMS.**

Mean Endpoints of jump trials with TMS can be seen in Table 4-2

**Table 4-2 Mean endpoints of initial and reproduced movements in mm from center (and standard deviations) in TMS conditions**

<table>
<thead>
<tr>
<th>Movement</th>
<th>Left</th>
<th>Center</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aware</td>
<td>Unaware</td>
<td>Aware</td>
</tr>
<tr>
<td>Initial</td>
<td>-12</td>
<td>-18</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>(46)</td>
<td>(39)</td>
<td>(32)</td>
</tr>
<tr>
<td>Reproduced</td>
<td>-30</td>
<td>-24</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>(36)</td>
<td>(38)</td>
<td>(34)</td>
</tr>
</tbody>
</table>

To establish whether online corrections had been made in the initial movements when TMS was administered, the same tests were conducted on the endpoints of TMS jump
trials. These trials were compared with those trials in which TMS was administered but the target remained in the center and did not jump. (A family wise Bonferroni correction was performed, and so the significance level for the following t-tests is .0125). Again, all differed significantly from the center point trials regardless of whether the participant was aware (left: $t_4 = 7.88, p = .001$, right: $t_4 = -6.08, p = .004$) or unaware (left: $t_4 = 8.09, p = .001$, right: $t_4 = -7.51, p = .002$) of the target shift. It can therefore be concluded that participants still made online corrections to their movements when TMS was administered.

The effect of awareness on the extent of these corrections was then considered. (A family wise Bonferroni correction was performed, and so the significance level for the following t-tests is .025). For trials in which TMS was administered no significant difference was found between the endpoints of aware and unaware trials for jumps to either the left ($t_4 = 1.60, p = .18$) or the right ($t_4 = .60, p = .58$). That is, in trials in which TMS was administered, participants were just as efficient in correcting to targets regardless of whether they were aware of the jump.

Finally the effect of awareness of the target jump on motor awareness was again considered by comparing the endpoints of the reproduced movements. The endpoints of the TMS jump trials in which participants reported being aware of the jump were compared with their equivalent counterpart when they reported that there was no jump. (A family wise Bonferroni correction was performed, and so the significance level for the following t-tests is .025). As for the non TMS trials, no significant differences were found (left: $t_4 = -1.73, p = .16$, right: $t_4 = .98, p = .38$)
Comparison of End Points of Initial Movements With and Without TMS.

In order to establish whether TMS had any effect on the endpoint of these initial movements, the endpoint of the trials in which TMS was administered were compared with their no TMS equivalent (see Figure 4.3). (A family wise Bonferroni correction was performed, and so the significance level for the following t-tests is .01). None were found to show a significant difference regardless of whether the participant was aware (left: \( t_4 = -1.87, p = .14 \), right: \( t_4 = -.38, p = .73 \)) or unaware (left: \( t_4 = .24, p = .82 \), right: \( t_4 = .19, p = .86 \)) of the target shift. In addition, there was no effect of TMS on the center point trials (\( t_4 = .91, p = .42 \)). It would therefore appear that TMS had no effect on the endpoint of any movements.

Figure 4.3 Mean endpoints in jump trials

---

**Initial**

- **TMS**
  - ■
  - ◆

- **No TMS**
  - ■
  - ◆

---

**Reproduced**

- **TMS**
  - ■
  - ◆

- **No TMS**
  - ■
  - ◆

---

Horizontal Deviation (mm)

- ■ Aware of target shift
- ◆ Unaware of target shift

Target start position:
- ●

Target end position:
- ■
Note: A negative value indicates a leftward deviation. A positive value indicates a rightward deviation. As there is no jump to be aware of in Center trials there is no aware/unaware distinction in that condition.

However, it may be that TMS successfully disrupted the online correction in a subset of trials. Such an effect may not be visible in standard statistical testing. The individual endpoints of the initial movements of each participant were examined to establish whether such a pattern was present (see Figure 4.4).

If such a pattern were present it would be visible in the form of a subset of TMS jump trials within the center point range. Figure 4.4 shows no such pattern. There is no visible difference between the endpoints of TMS and non TMS jump trials.
Figure 4.4 Endpoints of jump and center trials for each participant, with and without TMS

Note for X: 0 = actual center position
A negative number indicates a leftward deviation
A positive number indicates a rightward deviation
Discussion

End Points of Initial and Reproduced Movements without TMS

The mean endpoints of the initial movements for the jump trials with no TMS were found to be significantly different from the equivalent center point trials. No significant difference was found between those trials in which the participants reported that they were aware of the target shift, and those in which they were not. This is a replication of the results seen in Experiment 2 and others (Pélisson et al., 1986; Desmurget et al., 1999) that found that participants can make an online correction to a target shift regardless of whether they are aware of that target shift. In addition, no significant difference was found in the end points of the reproduced movements, regardless of awareness of target shift. This is again a replication of the results seen in Experiment 2, participants reproduce the correction in their trajectory even when they reported that they were unaware of the target shift that caused it.

End Points of Initial and Reproduced Movements with TMS.

The mean endpoints of the initial movements for the jump trials with TMS were found to be significantly different from the equivalent center point trials. No significant difference was found between those trials in which the participants reported that they were aware of the target shift, and those in which they were not. In addition, no significant difference was found in the end points of the reproduced movements in the TMS trials, again, this was regardless of awareness of the target shift.
Comparison of End Points of Initial Movements with and without TMS

Finally, a direct comparison of the endpoints for the initial movements for those jump trials with and without TMS showed no significant effect of TMS. Further, a visual inspection of the endpoints of each trial for each participant showed no evidence that any subset of jump trials was affected by the TMS pulse. This study therefore failed to replicate the findings of Desmurget et al (1999) that TMS to the PPC suppresses automated online corrections to a target shift.

General Conclusions

As the basic effect of correction suppression with TMS was not replicated it was not possible to test the original hypotheses regarding how such suppression would affect motor awareness. There are a number of possible reasons why the basic effect was not replicated. Desmurget et al (1999) were using a custom, iron core TMS coil. Although they state that the field it produces is equivalent to that of the figure of eight coil used here, there may have been important differences between the fields produced. Notably, the field from their coil may have penetrated deeper into the parietal sulcus or spread further into the surrounding tissues than the coil used here.

As stated previously, the coil used by Desmurget et al (1999) was a custom coil with an iron core. This is believed to produce a more directed field, but also a more powerful one. Although Desmurget et al performed a number of control conditions, it is still possible that the effect they reported is due to some non specific effect. Some of the control conditions were only conducted on a subset of an already small sample and so other participants may have been showing muscular responses to the stimulation. It is
also unclear what, if any, counterbalancing was used on the control conditions. If the experimental conditions were run first then the effect could be explained by a startle or blink response that had attenuated by the time the control conditions were tested as the participants became more familiar with the effects of the TMS pulse.

It may also be that this study failed to correctly localise the coil position. Although the localisation method used by Desmurget et al (1999) was followed, in this study the participants were not scanned afterwards to ensure the positioning had been correct. Desmurget et al noted that at least one of their participants had been stimulated slightly more medially than the others. Perhaps then, the participants here were stimulated sufficiently far from the intended site as to no longer cause the intended effect.

However, it should be noted that in the original study the basic effect does not appear to be universal. One of the five participants showed no correction suppression effect following TMS. As both that study and this used a small number of participants it may be that one or both were subject to sampling error and that the participants tested were not representative of the general population.

It is unfortunate that it was not possible to reproduce the basic effect, as the paradigm would offer a potentially rich source of data relating not only to the basic corrections, but also to participants’ awareness of them. As such, it would be worth pursuing this topic further. It would be helpful to establish what the cause of the failure to replicate was. If it can be traced to the coil for example, then an investigation into the differences between the fields produced could shed light on the precise neural location that is
critical in this task. If future research shows that the effect seen by Desmurget et al (1999) is robust and can be replicated under various conditions then the manipulation attempted by this experiment could be run again.

However, in the event that this is not possible, alternative methods could be considered. In particular it would be of great interest to establish what motor awareness is reported by patients who cannot produce the automatic corrections seen here, such as that described by Gréa et al (2002). What movement do these patients think they have made when they fail to correct following a target shift?
5. Experiment 4: Chronostasis and awareness in pro and anti saccades

Introduction

Experiment 1 used movement reproduction in a variety of pointing tasks. It was found that participants showed attenuated awareness when pro pointing, but were fully aware when anti pointing. It was therefore argued that intention plays a major role in awareness. In order to test this claim it is necessary to investigate the role of intention in another movement. One possibility is saccadic eye movements. Although they are clearly a very different type of movement, saccades can be manipulated along similar dimensions to a pointing movement.

As with pointing movements, reactive saccades can be made towards a peripheral target (pro saccade) or away from it (anti saccade). Pro saccades occur quickly after the stimulus onset. Anti saccades typically have a slower onset (Cherkasova, Manoach, Intriligator, & Barton, 2002). Clearly these conditions are comparable with pro and anti pointing. However, saccades differ in that the intentional component occurs prior to movement onset, rather than online as with pointing movements. That is, a delay occurs prior to an anti saccade being initiated (Cherkasova et al., 2002). Whilst the process is not yet fully understood, it is likely that prior to saccadic onset the automated or reflexive movement towards the target must be inhibited, and a new saccade planned towards the opposite location. As a result the automated and intentional components of
the movement dissociate naturally to some extent. Compare this with pointing movements where the target jump occurs mid-flight and so the intentional component (anti point) occurs during the ongoing movement. However, if the assertion that intention plays a major role in awareness is correct, a difference should still be seen in awareness of an anti saccade with a strong intentional component as compared with the relatively automated response of a pro saccade.

This then leaves the question of how to investigate participants' awareness of their saccades. Although movement repetition was successfully used in Experiments 1, 2 and 3 it may not appropriate for investigating awareness of saccades. It is not clear to what extent people have voluntary control over the precise path of a saccade, or what proprioceptive information is available to them about their saccade trajectory (see Weir (2000) for a review of the debate about proprioceptive inflow from extraocular muscles). It therefore seems unlikely that participants would be able to accurately reproduce a saccade. An alternative paradigm would therefore be preferable.

The intentional component of an anti saccade is reflected not in the path or duration, but in the pre saccade delay. Therefore, a timing paradigm may be a suitable method. Timing paradigms have previously been used to investigate saccadic illusions. When a participant saccades towards a target that moves constantly, but discretely and predictably, (e.g. the second hand on a clock) it sometimes appears to have briefly stopped, so that it appears to take longer to reach its next location. This effect has been called Chronostasis (Yarrow, Haggard, Heal, Brown, & Rothwell, 2001). Yarrow et al (2001) investigated this effect using a temporal discrimination task. Here, participants are asked to judge if the first duration is longer or shorter than subsequent one second
durations. They found that participants judged them as equal when the first duration was significantly shorter than those that followed. Yarrow et al (2001) argued that the effect occurs because participants backdate their perceptual awareness to a moment prior to their saccade onset.

The Chronostasis effect is of interest here for a number of reasons. First, it provides a potentially useful timing paradigm. However, it also draws on many concepts that were explored in Experiments 1, 2 and 3. Yarrow et al (2001) incorporated a saccadic suppression task into a control experiment. On a subset of trials the target counter was moved during the saccade. It was found that the Chronostasis illusion was broken when participants were perceptually aware of the counter jump. Yarrow et al (2001) argued that the temporal illusion was dependent on perceived spatial constancy, but they did not explore the results further. Both Yarrow et al (2001) and other researchers (Thilo & Walsh, 2002) have noted that Chronostasis shares a similar time course to saccadic suppression, which has previously been proposed as a mechanism for perceptual continuity during eye movements (Bridgeman, Van der Heijden, & Velichovsky, 1994).

A further intriguing aspect of the Chronostasis effect is that the temporal predating appears to map onto the saccadic duration quite accurately. Therefore, although the illusion initially appears to be perceptual, the effect actually seems to be driven by motor performance. This can be compared with the results of the pointing studies in Experiments 2 and 3. In those Experiments it was shown that motor performance and perceptual awareness can dissociate. However, the data from Yarrow et al (2001) is probably closer to the real life situation, in which perceptual awareness and motor performance are closely linked. The Chronostasis paradigm therefore creates an unusual
situation; a test of perceptual awareness that also provides a direct measure of motor performance, and may give an insight into motor awareness.

We know from Experiments 2 and 3 that perceptual awareness and motor performance can dissociate. However, in the Chronostasis paradigm perceptual awareness appears to be dependent upon motor performance. That is, the perceptual effect is back dated to a time just prior to movement onset.

As previously discussed the intentional and automated components of a saccade dissociate naturally. The intentional component occurs pre saccade whilst the automated component is reflected in the duration of the saccade. Depending on where within the processing stream the Chronostasis effect occurs, a different pattern of awareness may be seen in anti saccades when compared with pro saccades. If it arises prior to the specification of the saccadic response, then as response time increases with anti saccades, so should the Chronostasis effect. If however, intention does play a critical role in awareness, then it may be that the perceptual illusion will only back date to the start of the automated component. In this case there would be no difference in the size of the Chronostasis effect between pro and anti saccades. Finally, it may be that introducing an intentional component will break the illusion entirely, much as spatial discontinuity of the target does (Yarrow et al., 2001).

As discussed in earlier chapters, it can be problematic to make inferences about motor awareness based on perceptual awareness. However, in this case there is a known relationship between motor performance and perceptual awareness. In addition, the data from Experiment 1 suggests a clear prediction that the intentional component of the
movement should fully enter awareness and therefore not be subject to the Chronostasis illusion. It therefore seems reasonable to test this prediction, whilst remaining aware of the limitations of this approach. Experiment 4 therefore combines the Chronostasis paradigm of Yarrow et al (2001) with an anti-saccade task.
Method

Participants
27 participants were tested in total. The 2 investigators took part along with a further 25 volunteers who were each paid £7.50 to participate. The data from one participant was discarded due to high variability in their response times (greater than 3 SDs). Of the remaining participants, 15 were male with a mean age of 30.5 (SD 7.8).

Apparatus
A 22” CRT colour monitor was arranged 41 cm in front of the participant. The monitor refreshed at 60 Hz, eye to screen distance was maintained using an adjustable chin rest. Horizontal eye movements were recorded from the left eye using an infra-red eye tracker (Microguide 1000 spectacles, low-pass filtered at 40 Hz) and sampled at 200 Hz.

Stimuli subtended 1.1° and were presented on a white background. Peripheral fixation crosses were black, the central fixation cross was red. The post saccadic stimulus was a black open circle and the comparison stimulus was a red open circle. Open squares subtending 3.3° were used for peripheral targets. The experiment was controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

Design
A single factor, 3 level, repeated-measures design was used. The 3 conditions were; pro saccade, a reactive saccade of 20° to a peripheral target; anti saccade, an identical saccade made in a direction opposite to a peripheral target; control, constant fixation at matched eccentricity (±20°). Conditions were presented in blocks, with six blocks per
condition. One block from each condition was completed in turn; the order was counterbalanced across participants for the first 24 volunteers. The remaining two participants were the investigators who completed the 18 blocks (along with a further 12 blocks from two extra conditions not reported here) in a random order.

A velocity criterion was used to calculate saccade start/end points; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. If the first detected saccade travelled less than 90% of the total distance recorded (summed across all detected saccades), the trial was excluded on line and immediately repeated. Therefore, all trials with a detectable anti saccade error (when participants initially moved their eyes in the wrong direction) were rejected.

The primary statistical analysis will be a 3 level (pro saccade, anti saccade, control) repeated measures ANOVA on the duration of the “subjective seconds” (see Procedure). A significant main effect of condition will be investigated further using two orthogonal planned contrasts. The first will compare the control with the pro and anti saccade conditions. The second will compare the pro saccade and anti saccade conditions.

### Procedure
For saccade blocks black crosses were displayed 20° to the left and right of a central red cross. In pro saccade blocks, participants fixated the red cross and initiated the trial with a mouse key press. 500 ms later a black outline box appeared around one or other peripheral cross, directing the participant to make a speeded saccade in that direction. The box appeared randomly to the left or right on each trial. In anti saccade blocks the same sequence of stimuli was used, but participants were required to saccade to the
cross around which the box had failed to appear (i.e. in a direction opposite to it). Eye movement triggered the black cross to be replaced with a circle when the saccade had travelled one fifth of the distance to target. The circle remained on screen for 400-1600 ms. It then disappeared, to be replaced by a red circle (the comparison stimulus) after 500 ms. Participants indicated whether the time they saw the first circle was longer or shorter than that for which the comparison circle was displayed. The duration of the first circle was controlled by an adaptive algorithm. Blocks finished when the algorithm terminated. The duration of the post saccadic stimulus at this time was recorded.

In control (constant fixation) trials, participants initially fixated a peripheral cross at equivalent eccentricity. It was blanked 400ms after the participant’s mouse key press, then replaced after a further 100 ms by the to-be-judged circle, with subsequent stimulus presentation and participant responses as per saccade trials. Position of this fixation cross alternated every trial.

Blocks were of variable length, typically 6-20 trials (excluding those rejected). The average of the block termination values in each condition was calculated. This gave a measure of the participant’s “subjective second”. This was the duration of the post saccadic stimulus that the participant rated as being equal to the subsequent comparison stimulus of one second. In the saccade conditions, each estimate was corrected post hoc to match the time the first circle was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change to a circle (averaged across all six blocks). The experiment took around one hour to complete.
Results

Saccades

A significant difference of 3 ms ($t_{(25)} = -3.65, p < .001$) was found between the duration of pro saccades (58 ms) and anti saccades (61 ms). A predicted and significant difference of 61 ms ($t_{(25)} = 6.52, p < .001$) was also found for saccadic onset. RT for pro saccades was 274 ms on average and 335 ms for anti saccades.

Time Estimates

Mean corrected ‘subjective second’ time estimates for the 3 conditions are shown in Figure 5.1. These provide a measure of the Chronostasis effect as they show how long the post saccadic stimulus had to be displayed, in order for the participant to rate it as being equal to the subsequent comparison stimulus of one second. Values below 1000 ms indicate a Chronostasis effect, namely that the post saccadic stimulus onset is perceived to begin at or around the time of saccadic onset, rather than at saccadic offset.

The control estimate (1063 ms) is slightly higher than has previously been reported (Yarrow et al., 2001). The mean judgements did not differ significantly from 1000 ms in any condition, (control: $t_{(25)} = 1.78, p = .87$, pro: $t_{(25)} = -.57, p = .57$, anti: $t_{(25)} = -60, p = .55$). However, the relationships between the judgements are more relevant for measures of subjective timing and will now be considered further.
A one way ANOVA indicated a significant main effect of condition ($F_{(2,50)} = 5.45$, $p = .007$). Planned contrasts showed that the control condition differed significantly from the pro and anti saccade conditions ($F_{(1,25)} = 16.34$, $p < .001$). There was no significant difference between the pro saccade and anti saccade conditions ($F_{(1,25)} < 1$, $p = .99$).

These data demonstrate a significant Chronostasis effect of 90 ms in the pro and anti saccade task when compared with the Control condition. However, the size of the effect is identical for both pro saccades and anti saccades.
Discussion

As expected a significant difference was found in response times; anti saccades took 61 ms longer than pro saccades (Cherkasova et al., 2002). A small significant difference of 3 ms was also found in saccade duration across the two conditions. A significant Chronostasis effect of 90 ms was found. This was identical in the two saccade conditions.

This pattern of results demonstrates that the Chronostasis effect arises after the respecification of the saccadic response in the anti saccade tasks. More interestingly however, it provides further support for the argument proposed following Experiment 1; that intention plays a critical role in awareness. The Chronostasis effect size was identical in the pro and anti saccade conditions. This indicates that the effect is being back dated to a component that is the same for both conditions. The figure of 90 ms suggests that this occurs at some point just prior to saccadic onset and therefore incorporates the automated portion of the saccadic movement. However, it does not extend back to incorporate the additional pre saccade delay seen in the anti point trials; the intentional component of the task.

As discussed earlier, one must always be careful when extrapolating motor awareness from perceptual awareness. It cannot be concluded with any certainty that participants are aware of the duration of the pre saccade delay in anti pointing, or unaware of the duration of their saccades. However, it does demonstrate that the automated component of the movement can cause a perceptual illusion, whilst the intentional component does
not. That is, participants did not recategorise the process of intention as perceptual awareness, only awareness of the automated motor component was suppressed. Given that this pattern of results is so similar to that predicted by Experiment 1, parsimony suggests that motor awareness is likely to mirror this pattern, at least to some extent. However, more research would be needed before this could be determined.

Despite this, the result still raises a number of interesting points for this thesis. Experiments 2 and 3 demonstrated that perceptual awareness can dissociate from both motor performance and motor awareness. However, this only seems to occur under certain laboratory conditions. In everyday life the relationship is likely to be far more complex. This data may be able to give us some insight into that relationship. It has long been known that vision can dominate touch when conflicting information comes from the two senses (Rock & Yeshiva, 1967). Yet when the Chronostasis effect occurs, motor behaviour dominates vision. That is, the perceptual illusion occurs because the perceptual experience is back dated to a point prior to movement onset. Why should the normally dominant sense of vision be subject to illusion under these conditions?

It has been argued that the illusion may be a direct result of the effects of saccadic suppression (Yarrow et al., 2001; Thilo & Walsh, 2002). Saccadic suppression allows the participant to maintain a stable visual scene during eye movements (Bridgeman et al., 1994), at the expense of additional visual information. As a result, they are left with 'gaps' in their knowledge of the visual scene. The Chronostasis effect may be one of the mechanisms that fill in these gaps as the participant simply assumes that the visual scene they see at the end of the saccade already existed at the start of their movement. This suggestion is compatible with Yarrow et al's (2001) finding that the effect is broken.
when participants become aware of movement in the visual scene. The extent to which
participants are actually unaware of movement in their visual scene during a saccade
and how visual field information is computed and integrated during eye movements is
still not fully understood (Melcher & Morrone, 2003). However, both saccadic
suppression and the Chronostasis effect clearly indicate that perceptual awareness is
lacking, or at least attenuated during saccades. In addition, the Chronostasis effect
suggests that under these conditions participants rely at least partially on motor
awareness to fill in the gaps. In this case, by backdating visual perception to the point at
which they were aware of their saccadic onset. It has previously been shown that
participants generally report that they believe they move earlier than they actually do
(Libet et al., 1983; McCloskey, Colebatch, Potter, & Burke, 1983). That is, motor
awareness of movement onset typically precedes actual movement onset by some small
period. This is clearly compatible with the predating seen in Yarrow et al’s (2001) data,
and reported in this experiment, where the Chronostasis effect is back dated to a
temporal point just prior to movement onset. It is quite possible that the marker being
used is the participant’s motor awareness of their saccadic onset.

If this is the case then it would explain why the Chronostasis effect is back dated to a
point beyond movement onset, but why it does not extend back to incorporate the
additional pre saccadic delay seen in anti saccade tasks. This then raises more questions
about the nature of motor awareness. Intention and planning have tended to be presented
here as a single unitary process. However, it is more probable that these are actually
separate stages and may have different neural substrates and different time courses.
They may even break down further into additional, but as yet unidentified, stages.
Therefore, although it has been demonstrated that motor awareness is linked to
intentional processes, it is not yet clear precisely which stage is most important. To what extent does awareness extend to pre motor planning? Do participants have motor awareness of the duration of their movements? Is an intentional component necessary for awareness of this period? Unfortunately, due to the reliance on a measure of perceptual awareness in this experiment, it is not possible to consider these questions in more detail with the current paradigm. Therefore another paradigm will be necessary to consider these questions more fully.
6. Attentional cueing tasks and timing paradigms

In experiments 1, 2 and 3 the experience of action has been investigated across a variety of pointing experiments. It has been established that there is a distinct form of motor awareness that is available for report through the use of movement repetition. In addition, it has been shown that this awareness can be attenuated by manipulating a variety of factors. The participant’s intention has been shown to be a key feature of this attenuation.

Experiment 4 demonstrated that intention plays a similar role in awareness of saccades. These were also found to be prone to attenuation through experimental manipulation of intention. Here, however, a timing rather than repetition paradigm was used. Rather than providing a direct measure of the participant’s experience, it allowed inferences to be drawn about the extent of their underlying awareness. The next chapters extend and generalise these findings.

It is clear from these Experiments that there is still much work to be done in both of these areas. Both have received relatively little attention from psychological researchers and many questions have been raised that remain unanswered. However, these questions are beyond the scope and aim of this thesis. The primary aims of which are to characterise motor awareness and identify a number of practical methods with which it can be investigated. Therefore, rather than investigating these areas in any more detail, it is instead necessary to identify another method with which motor awareness can be
investigated. It would also be helpful to investigate another type of movement, to establish to what extent the conclusions drawn so far can be generalised.

The criteria for such a movement would be that it can be easily and reliably manipulated, ideally with well known intentional and automatic components. In addition, it needs to be quantifiable and measurable, both objectively for the researcher and for the participant to give a subjective report.

One possibility can be found in the work of Posner (1980). Whilst investigating attentional effects Posner (1980) developed a number of paradigms that satisfy these constraints. In particular he devised a number of cueing paradigms. The key feature of these tasks was that by manipulating a participant’s reorientation of attention towards or away from a stimulus, their Reaction Time (RT) to that stimulus could be expedited or delayed. These paradigms are of particular interest here because as well as filling the necessary criteria for automaticity, they also have an attentional component. This will allow further consideration of the role of attention in attenuating motor awareness, a possibility suggested by the results of Experiment 1.

Attention is a generic term for the directable mechanism(s) that allow people to select salient aspects of their environment for additional processing. Within that definition, attention can be divided into many sub-parts. The aspect that is to be investigated here is visual spatial attention, the selection of a specific location within the environment for further processing. Attention can be reoriented in a number of ways. It can be overt, a physical shift of receptors such as an eye or head movement, or covert, a purely internal shift (Posner, 1978) such as ‘looking out of the corner of your eye’. As suggested
above, it can also be automatic, an involuntary response to an unpredictable, salient stimulus or intentional, a deliberate voluntary shift prior to an expected stimulus. These are also known as exogenous (automatic) and endogenous (intentional) reorienting (Spence & Driver, 1996).

One of the earliest experiments that specifically aimed to manipulate endogenous (intentional) attention was conducted by Posner (1978). He presented participants with central cues that were followed by peripheral targets. The cues could be neutral (e.g. 'X') or directional. The latter would usually consist of an arrow indicating which side (left '<' or right '>') the target was most likely to appear on. He found that RTs to 'valid' directional cues (e.g. an arrow pointing right followed by a target on the right) were faster than those for 'invalid' cues (e.g. an arrow pointing right followed by a target on the left) whilst RTs for neutrally cued targets fell in between.

This cueing paradigm was adapted to investigate exogenous (automatic) attention. Here the cues used are peripheral and non-informative. They are generally presented briefly just prior to the target onset and at the target location. Instead of the participant actively reorienting their attention towards the indicated location, the cue captures attention reflexively and pulls it to that location automatically (Spence & Driver, 1994b). This occurs even though the cues are not predictive and it is not strategically advantageous for the participant to attend to them. Under these conditions however, the effects of the exogenous cues are similar to those seen for the endogenous cues. RTs to valid exogenous cues are fastest, followed by neutral cues with invalid cues showing the longest RT. Although the basic RT effect can be the same for both endogenous and
exogenous cues, they appear to be mediated by different pathways and have different underlying neural substrates (Coull, Frith, Buchel, & Nobre, 2000).

Although these attentional affects are robust and reliable, there is still some debate as to where the locus lies within the processing stream, and potentially regarding the relationship between attention and awareness.

Figure 6.1 demonstrates some of the stages at which the attentional effects could occur.

**Figure 6.1 Actual and Judged Reaction Times**

**External Events**

- Stimulus
- Motor response
- Actual Reaction Time
- Judged Reaction Time
- Detection latency
- Stimulus arrival
- Action plan
- Perceived completion
- Stimulus processed
- Motor output

**Internal Events**

Posner (1980) claimed that attended events enter perceptual awareness with a shorter latency than unattended events, and so localised the effect as occurring prior to stimulus detection. He proposed that this difference was due to selective attention filtering out unexpected events causing a detection latency. This view naturally produces a link
between selective attention and temporal awareness, which will be crucial to the next chapters of this thesis.

This link has received considerable support through the phenomenon of Prior Entry. A concept that goes back to some of the earliest theorists (Titchener, 1908; Boring, 1929) and is still used in current research (Shore, Spence, & Klein, 2001; Spence, Shore, & Klein, 2003). The basic tenet of prior entry is that attended stimuli are perceived earlier than unattended stimuli. A concept closely linked to Posner’s (1980) claims. The primary method for investigating prior entry has been the use of temporal order judgement tasks (TOJ). Here two stimuli are presented at similar latencies and the participant is asked which order they appeared in. The stimuli can be presented across spatial locations (Abrams & Law, 2000) or perceptual streams (Sternberg & Knoll, 1973) and the judgement can be which came first or which came second (Shore et al., 2001). The point of subjective simultaneity (PSS) is calculated, this is the point at which the participants show maximum uncertainty as to which came first. In all the above examples the underlying theory and findings are the same, the attended stimuli is judged as occurring prior to the unattended stimuli even when it actually occurs slightly later.

However, the idea is not without its detractors. Primarily, it has been argued that the effect is largely due to response bias, with participants simply reporting the attended side, especially when unsure (Frey, 1990; Pashler, 1998).

More recent studies have attempted to counter this argument. Notably, Shore et al (2001) used two methods to minimise confounds. They used an orthogonal cueing paradigm, where the decision to be made is orthogonal to the attentional cue. In this
case, a left/right cue followed by a decision about stimulus orientation. In addition, they asked both ‘which came first’ and ‘which came second’. Having controlled for these variables they still found prior entry effects, although, it was quite small for endogenous cues (17ms) but larger for exogenous cues (61ms).

However, whilst these findings suggest there is a prior entry effect, independent of response bias. It does not prove that it is the main cause of the RT effects seen in cueing paradigms, especially with the effect being relatively small for endogenous cues. As a result, other researchers have attempted to further quantify and localise the effect using alternative measures (Johnson & Haggard, 2003).

Johnson and Haggard (2003) argued that if an endogenous cue caused delayed detection then this should be reflected in the participant’s perceived time of stimulus onset. They used a simple response task to minimise response bias and the Libet (1983) timing paradigm for measurement. Here a participant is asked to judge the time of stimulus onset by means of a fast moving clock. Johnson and Haggard (2003) demonstrated a significant attentional cueing effect on reaction times (29ms). However, no significant effect was seen on the perceived time of stimulus onset. A small non significant difference was seen (11ms) but this was not sufficient to explain the response delay. They therefore localised the primary cause for the response delay as occurring after stimulus detection.

The Role of Stimulus Detection

How then, can these somewhat contradictory studies be reconciled? The long standing concept of Prior Entry has been shown to be present in these attentional tasks (Shore et
al., 2001) yet prior entry effects seem to be too small to explain the attentional effect on RT (Johnson & Haggard, 2003).

There are two main possibilities. First, there is more than one process involved, both of which are subject to attentional effects, and both of which contribute to the overall reaction time. When describing the cueing tasks Posner (1980) also gave a definition of ‘detection’;

Detecting (meaning) that a stimulus has reached a level of the nervous system at which it is now possible for the subject to report its presence by arbitrary responses that the experimenter may assign. These may be verbal (‘I see it’) or manual (pressing a key). (Posner, 1980 p4).

This statement combines the numerous stages involved in the task into a single event. That is, the visual stimulus impinging on the retina, passing through cortical processing during which it is identified and the preparation of a response, are all collapsed into a single event called ‘detecting’. At some point within this process the stimulus reaches the level described above and then it has been ‘detected’.

In one sense this is correct, this single event is the reaction time. This is the period during which the attentional effects occur and therefore the interval of interest in these tasks. However, as previously shown in Figure 6.1 there are various stages at which the effects could occur. Attentional effects on behaviour could occur due to changes in stimulus detection, central stimulus-response association or response processing. A delay in any one of these stages could cause a delayed reaction time. It may also be that
multiple stages are affected. These would be amalgamated across the course of the response into a single response delay.

Posner (1980) would presumably place detection as having occurred when the action plan was formulated. However, Prior Entry effects are supposed to occur much early than this. It is claimed to occur prior to the stimulus’ arrival (Shore et al., 2001). In Figure 6.1 this would be the segment labelled ‘detection latency’. Johnson and Haggard’s (2003) study demonstrated that the delay identified at this stage was not sufficient to explain the response delay.

**The Nature of Time**

However, there is a second possibility that could explain the apparent contradiction. It may be that the two methods (TOJ versus Libet) are measuring different things. Although at first both appear to be using simple timing paradigms to measure stimulus onset, they are not necessarily measuring the same sort of ‘time’.

Within philosophy it has long been argued that time can be conceptualised as having multiple streams. The two primary streams are A, the absolute stream and B, the relative stream (McTaggart, 1927). A is characterised as past, present and future, B is concerned with relative values such as before and after. The critical feature of this concept is that the two streams are independent, though related. If Event X occurs before Event Y within Stream B, this event pair could happen at any point within Stream A. Therefore, knowing when an event occurs in relative time (Stream B), tells us nothing about when it occurs in absolute time (Stream A).
The primary feature of the A stream is that it is quantifiable, an event is not only classified as past, but can also be quantified as having occurred 1 minute, 2 days, 3 weeks or 17 years ago. These positions change with the perspective of the viewer, in the sense that they are all referenced to ‘now’, so they are to some extent fluid. An event that occurred 1 minute ago will soon have occurred 2 minutes ago, etc. However, as long as the perspective of the viewer is consistent within a given time frame, then a measure of the A stream should be equal to a measure of their experience of the passage of time. Compare this with a measure that relies on B stream where the primary measure is the order of presentation rather than the timing.

Claims that time should be conceptualised as having multiple streams is not just a theoretical or philosophical concept. It is vital to psychological understanding of how people experience time and the mechanisms that underlie it. It has also led to more subtle distinctions such as theories of temporal orientation (knowing what day of the week, month or year it is). For example, time estimation and temporal orientation have since been found to be dissociable and to have different neurological substrates (Benton, Van Allen, & Fogel, 1964).

The distinction between A and B streams can clearly be seen in traditional measures of prior entry using TOJ. Asking a participant which external event occurs first, tells us little about when they experienced either of those events or how long they perceived the duration to be. It is a pure measure of the B time stream. Conversely, the Libet clock method measures only what time a particular participant experiences a particular stimulus. It is therefore a pure measure of the A time stream. Although both are equally valid measures, it is perhaps not surprising that the findings differ. However, it would
suggest that one should be wary of extrapolating when something was experienced in the A stream from a measure of B stream, and vice versa.

This difference is critical in deciding an appropriate measure for the following studies. The aim here is to attempt to measure a participant’s experience of how long an event lasts or when an event occurred rather than which stimulus appeared first. It is clear that any temporal measure that relies primarily on the B stream cannot provide us with sufficient information with which to quantify their experience. For that reason a measure of the A stream is required. In addition, if we hope to use these studies to further investigate the locus of attentional effects on behaviour, the secondary aim of this thesis, then the method chosen must also allow participants to precisely quantify their experience of their RT.

There are a number of psychological measures which capture A stream time, and are thus appropriate for studying the relationship between attention and temporal awareness. Four of which are commonly used in humans (Bindra & Waksberg, 1956). Temporal discrimination; where two stimuli are given and participants have to judge which is longer/shorter. Verbal estimation; where participants are asked to give a precise verbal estimation of the length of a given stimulus. Temporal production; where participants are asked to produce a duration of a given length. Temporal reproduction; where participants are given a stimulus and asked to produce a duration of identical length.

A variant of temporal discrimination was used in Experiment 4 where participants had to compare the duration of the first visual stimuli with the following standard duration.
This gave a measure of perceived time of stimulus onset. From this it was possible to make inferences as to what knowledge they had of their eye movement. Temporal interval bisection, is another variant of temporal discrimination. It is known that all four methods utilise similar neurological pathways and structures (Lalonde & Hannequin, 1999) and that they produce broadly similar results (Wearden, 1999; Wearden, 2001). It therefore seems reasonable to assume that they are tapping broadly similar representations.

Temporal discrimination is a hybrid measure of A and B time streams, therefore it would not be appropriate. Neither would temporal production, as a duration, the participants own RT, has to be judged. Temporal reproduction is essentially a combination of verbal estimation and temporal production. Although it would be an appropriate measure it adds an additional layer of complexity, and therefore another potential source of confound or variability. The remaining method, verbal time estimation (VTE) however, fulfils all the necessary criteria.

According to a comprehensive review by Axel (1924) the earliest uses of VTE were concerned primarily with the investigation of individual differences. Sex and age differences were commonly found. Typically men tended to under estimate intervals, whilst women tended to over estimate. Under estimation was also found to increase with age. However, the latter finding is still debated, and the evidence is far from clear. It has been claimed that older adults under estimate with VTE, but over estimate with production methods (Craik & Hay, 1999). Conversely, other researchers have claimed the reverse is true (Block, Zakay, & Hancock, 1998). It has also been noted that
participants are aware of the errors in their estimations, and can judge with some accuracy whether they have tended to under or over estimate (Bakan, 1962).

Although VTE is still used to investigate individual differences (Craik & Hay, 1999; Block et al., 1998) in recent years research has increasingly concentrated more heavily on investigating the variance within judgements. Critically, VTE has been found to consistent within a participant (Wearden, 2001). In addition, it has been found to conform to scalar timing (Wearden, 1999; Wearden, 2001; Droit, 2002).

Scalar timing is critical in any timing paradigm, as it accounts for the variance within estimations, whilst allowing the mean to remain accurate. It is based on Weber's law; scalar variance is defined as having occurred when the standard deviation of the judgements is a constant fraction of the mean (Wearden, 1999).

For the purposes of this experiment then, a repeated measures design will alleviate any concerns about individual differences. In addition, as long as any conclusions drawn are based on the relative differences between a participant's mean judgements, rather than on precise values, than the absolute accuracy of a participant need not be a concern either.

It is therefore proposed to combine the attentional cueing paradigms of Posner with VTE in order to measure participants' motor awareness of their RT. Furthermore, it is hoped that by doing so we will gain further insight into the locus of the RT effects caused by attentional cues.
7. Experiment 5: Awareness of response time in simple and choice attentional cueing tasks

Introduction

In 1978 Posner, Nissen and Ogden conducted an experiment as part of Posner’s ongoing chronometric studies of the mind. They considered how participants’ ability to detect changes in luminance was affected by advance knowledge of target location (Posner, Nissen, & Ogden, 1978). They used a simple response task (SRT); regardless of the nature or location of the stimulus the required response was always the same; to press a single key and measured reaction times (RT). Information about the likely location of the target was provided by a central cue at the beginning of each trial. The cue could be either neutral (‘+’), providing no information about target location, or directional (‘<’ or ‘>’). A directional cue would be valid (point to the correct location) for 80% of the trials, and invalid (point to the incorrect location) for 20% of the trials. Posner et al (1978) found a cued location/target location compatibility effect. Reaction times to validly cued targets were compared with reaction times to neutrally cued targets, a benefit of around 25ms was found. Reaction times to invalidly cued targets were compared with reaction times to neutrally cued targets, a cost of around 40ms was found. In later experiments these findings were extended to choice response tasks (CRT), in which the participants has to make a response decision based on some attribute of the stimulus. Similar effects were found (Posner, 1978).
These findings were influential at the time and have been shown to be highly reliable. As well as demonstrating the behavioural effects of attention they showed that visual fixation and locus of attention were dissociable. Posner (1980) claimed that the attentional effects he found in cueing tasks were due to a delay in stimulus detection; “Detecting means to be aware or conscious of the stimulus” (Posner, 1980, p4). This claim has received further support through the phenomena of prior entry (Shore et al., 2001). However, recent studies have shown that a delay prior to detection is not sufficient to explain the extent of the delay seen in the Reaction Time (RT) (Johnson & Haggard, 2003). This study was reviewed in detail in Chapter 6. In addition, although the doctrine of prior entry appears to support Posner’s (1980) theory, they are not entirely compatible. Specifically, they have very different definitions of ‘detection’.

Posner appears to consider stimulus detection to be the primary function of the task with an arbitrary response being a neutral and consistent indication of stimulus awareness. The locus of the attentional effect, speeded reaction times to validly cued locations or retarded reaction times to invalidly cued targets, is therefore placed prior to conscious detection of the stimulus. Implicitly, Posner also combines the numerous stages involved in the task into a single event.

Prior Entry however, has been defined as ‘a perceptual effect on arrival times attributable to attentional modulation’ (Shore et al., 2001, p205). This appears to place the effect at the earliest possible processing stage, stimulus arrival. From Posner’s (1980) position the delay could occur anywhere prior to a response being prepared. However, for the effect to be identified as being caused Prior Entry, it must occur prior
to stimulus arrival. To compare these positions we must first consider the basic effect (Figure 7.1).

Figure 7.1 Schematic of attentional effect on RT

Actual Reaction Time

Stimulus onset ➔ Invalid Cue ➔ Motor response completed

Valid Cue

It can be seen from Figure 7.1 that the basic effect is apparently quite simple. It takes a participant longer to react to an invalidly cued target than to a validly cued target (Posner et al., 1978). However, whilst the external events may be simple, the internal events are less straightforward. In reality, the RT is not a single event, it is an extended epoch bounded by two measurable events; the stimulus onset and the overt response. In the interval between these objective external events, a range of internal events, both objective and subjective, may occur (Figure 7.2).
Within Figure 7.2 it can be seen that the external events have analogues within the internal events, however they are not absolutely identical. For example, the stimulus does not instantaneously arrive at the participant’s senses. When it does arrive it must be processed, perhaps identified according to shape or location, a suitable action plan formulated and then initiated, resulting in an overt response. Posner (1980) defined detection as having occurred once the participant is able to make a response; this places the locus of the attentional effects at, or prior to, the formulation of an action plan. Prior Entry theorists place it prior to stimulus arrival (Shore et al., 2001). If the locus is prior to stimulus arrival, then both theories would be correct. Alternatively, it could be that the delay occurs after stimulus arrival, but during processing. This would rule out Prior Entry as the primary cause of the RT delay, but still support Posner’s claims.
However, it could also be that neither position is correct. The delay could occur at the response selection stage, a view favoured by late selection theorists (Deutsch & Deutsch, 1963; Lavie, 2001). In this case, a response may be pre-prepared for the expected target. If however, the cue is invalid, this response must then be inhibited and a new response selected. This argument has received support from functional imaging studies (Miller, 1998). Miller (1998) used a choice reaction time task and considered the lateralised readiness potentials (LRP). That is, the differential electrical activation that occurs in each hemisphere prior to a movement in a lateralis CRT. On an invalid trial activation levels were first seen to increase in the hemisphere contralateral to the cued side. This then decreased and activation on the ipsilateral side rose. Miller (1998) claimed that this activation pattern suggested that faster responses were indeed caused by advance preparation of the probable response and that slower responses appeared to be caused by having to first inhibit the prepared response before beginning the correct reaction.

In addition, all of the above explanations rest on the assumption that the stimulus processing stream is serial. This assumption is by no means universally accepted. Pashler (1998) argued that the various processing stages may occur in parallel. This is compatible with current theories in neuroscience where it has been proposed that at least two pathways (ventral and dorsal streams) are involved in the identification of, and response to, visual stimuli (Goodale & Milner, 1992; Goodale et al., 1991). In this case, the response could be mediated by one pathway and might be speeded or slowed by attentional effects, whilst detection might use the alternative route, and remain unaffected.
Finally, an alternative but compatible theoretical model, comes from the work of Neumann (1990). Neumann dissociated motor responses from conscious awareness, and suggested that conscious detection of a stimulus does not necessarily influence the response. Direct parameter specification (DPS) was proposed as a way in which a stimulus could elicit a response without having first undergone conscious identification. This is contrary to Posner’s (1980) claims that detection of a stimulus is equal to being consciously aware of it, and also that a detection delay will cause a response delay. Studies of DPS have also found that for primed stimuli, at least part of the effect occurs at the response rather than the detection stage (Neumann & Klotz, 1994). If this can be shown for a primed stimulus that never reached conscious awareness, it may also be seen in responses to cued stimuli that did.

Therefore, localising the attentional effect may give us further insight into the nature of the processes underlying these tasks, supporting or discounting the various theories. Conversely, by empirically testing the predictions based on these approaches it may be possible to test those theories, thus aiding the localisation of the effect. The predictions to be considered here are how the attentional effects on behaviour will be reflected in participants’ awareness of their own RT.

A participant can only judge their RT from the time a stimulus arrives at their senses, to the time they perceive that they have made a response. That is not to say that these are necessarily the events that they would base their judgement on, but that these are the earliest and latest possibilities. Stimulus arrival is identified as the earliest possible measure because a participant can not be aware of how long a stimulus has been present prior to its arrival. Perceived response is the latest possible stage, as at this point the
participant believes they have completed the task, and that their movement has been
initiated. It is known that participants tend to believe they move earlier than they
actually do (Libet et al., 1983; McCloskey et al., 1983). It also takes some period for a
stimulus to arrive, and this is the stage at which the Prior Entry effect occurs, according
to some theories (Shore et al., 2001).

Figure 7.3 Schematic showing Prior Entry effect on Judged Reaction Time (JRT)

It can be seen in Figure 7.3 that a Prior Entry effect would increase the detection
latency. However, this delay is not reflected in the participant’s awareness, and
specifically in the Judged Reaction Time (JRT), which remains the same across cue
conditions. If the time at which a participant experiences stimulus arrival is recorded, it
should be found to arrive later for invalidly cued targets than for those with valid cues.

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Johnson and Haggard (2003) tested this prediction directly. They asked participants to use a Libet-type clock to report the time of stimulus onset in an Simple Response Task (SRT). They found no significant difference between perceived onset times for valid or invalidly cued stimuli. Although a small non-significant effect was seen at this stage, it was not sufficient to account for difference in RT. Unfortunately their measure was not sensitive enough to establish whether the delay was reflected in the participant’s perception of their motor response.

Previous research has also shown that participants’ awareness of the time of their motor response often occurs prior to their actual motor output (Libet et al., 1983; McCloskey et al., 1983). It has been claimed that this awareness of having responded arises prior to the response actually being initiated. Haggard, Newman and Magno (1999) investigated this using the Sternberg effect in typing, whereby the reaction time for the first action of a sequence increases proportionally to the number of items in the sequence. By combining this with a Libet-type clock task, they were able to establish that participants were unaware of the increased latency of the initial item in longer typing sequences. Haggard et al concluded that the internal event that participants reported is located prior to ‘the assembly and dispatch of the motor command’ (Haggard, Newman, & Magno, 1999, p299), as this is the processing stage in the Sternberg model at which the sequence length effect arises.

Late filter theorists (Deutsch & Deutsch, 1963; Lavie, 2001) may argue that the RT delay caused by attentional cues also occurs at this stage. If so then it would occur after the participant’s awareness of their response. Judged RT would be independent of
attention as this is the latest possible stage at which they could measure their RT as having been completed, a delay at this stage could not be reflected in a participant’s judgement of their RT (see Figure 7.4). As previous research (Johnson & Haggard, 2003) has not yet ruled this out, it is still a possible locus for the attentional effect. On this view selective attention could operate primarily on late motoric processes, perhaps occurring after the response selection stage.

**Figure 7.4 Schematic showing delay occurring after motor awareness, outside of JRT**

Finally, the delay could occur elsewhere within the processing stream. That is, after stimulus arrival, but prior to the perceived completion of the motor response. In this case the cause of the delay could be accessible to the participant for self report. This would be shown by the participant judging their RTs to be longer for invalid rather than validly cued targets (see Figure 7.5).
Figure 7.5 Schematic showing attentional effect occurring during the Judged RT period

Cue onset

Stimulus onset

Valid

Invalid

Stimulus arrival

Actual motor output

Perceived completion of motor output

Motor delay

The three models presented here make clear predictions about different patterns in participants’ subjective awareness of their Reaction Times to valid and invalidly cued targets. It was therefore decided to investigate the traditional Posner attentional cueing paradigms (Posner, 1978; Posner et al., 1978; Posner, 1980) using Verbal Time Estimation of RT in order to help establish the locus of the attentional effect. Both simple (SRT) and choice (CRT) reaction time conditions were used in order to investigate whether different processes are at work in SRT and CRT, and also to establish whether any effects of motor awareness are generalisable across a range of tasks.
Method

Participants
15 volunteers were each paid £7.50 to participate. The data from one participant was discarded due to equipment failure. Of the remaining participants, 7 were male with a mean age of 24 (SD 4.31). All were non-psychologists to ensure that they were naïve about both the effects being studied, and the purpose of the experiment. All were right handed with normal or corrected-to-normal eyesight by self report.

Apparatus
The experiment was conducted in a quiet, well lit room. Participants sat at a desk with their finger(s) resting comfortably on the appropriate keys on a keyboard. The stimuli were presented on a laptop computer screen using a custom programme. The laptop was arranged directly in front of the subject with the screen at a distance of 30cm. Participants responded by pressing the appropriate key on the keyboard.

Design
There were three response conditions (see Figure 7.6); simple (participants made a keypress with the right index finger); finger choice (participants made a left/right decision with a keypress using the right index finger for ‘left’ and the right middle finger for ‘right’), hand choice (participants made a left/right decision with a keypress using the index finger of the corresponding hand).
The three response conditions were presented in separate blocks, block order was randomised across participants. In each response condition participants completed 16 practice trials and 130 experimental trials. Experimental trials were presented in a random order, and practice trials were discarded from all analyses. There were two target positions; left and right. There were three cue types; directional left ('<'), directional right ('>') and neutral ('+'). There were three validity conditions; valid cue, (target appeared on the side indicated by the cue), invalid cue, (target appeared on the opposite side to that indicated by the cue), or neutral cue, (no side was indicated). In all conditions the target could appear on either the left or right of the screen. (See Figure 7.7).
Figure 7.7 Cue validity conditions

1: Valid Cue 2: Neutral Cue 3: Invalid Cue

Note: the cue and target location are shown together here for clarity. They would not actually be simultaneously visible to the participant.

The target was presented on each side on 15 trials for both invalid and neutral cues, making 30 trials for each of those validity conditions. The target was presented on each side on 35 trials with a valid cue, making 70 trials in that validity condition and a total of 130 trials. There was a break after every 25 trials, in addition, participants could stop the experiment and rest after any trial.

It is probable that there will be an effect of target position. For example, right handed participants will respond faster to rightward targets, as they will be using with their dominant hand. However, such effects will be equally distributed across conditions and
are not of interest in this experiment, therefore all data will be collapsed over target position. Two measures will be investigated, Actual Reaction Time (ART) and Judged Reaction Time (JRT). A 3 (simple response, finger choice response, hand choice response) * 3 (valid cue, invalid cue, neutral cue) repeated measures ANOVA will be conducted on each measure. Significant main effects of response condition will be investigated further using two planned contrasts comparing simple response with finger and hand choice response conditions, and finger choice with hand choice. Significant main effects of cue validity will be investigated further using two planned contrasts comparing the neutral cue conditions with valid and invalid cue conditions, and valid with invalid cue conditions.

**Procedure**
Participants were advised that a directional cue would be valid 80% of the time. They were instructed to keep their eyes fixated on the box in centre of the screen, but to direct their attention to the side indicated by the cue. When a neutral cue was presented they were advised to attend to both possible locations, as they were equally probable. They were asked to respond to the target by pressing the appropriate key as quickly and accurately as possible. After making their response they were asked to estimate their reaction time to the nearest ms. Participants were encouraged to be as accurate as possible and to avoid repeatedly using the same numbers.

A fixation box was displayed in the centre of the screen, and remained on throughout the trial. After a 1000ms delay a cue would appear within the box for 350ms. The cue would clear and a delay (randomised between 1000-1350ms) followed. A target would appear and remained on screen until the participant responded with a key press. The
target would clear and the participant would give an estimation of their reaction time (see Figure 7.8).

Figure 7.8 Schematic showing time course of a trial
Results

A number of trials were excluded from analyses. These are broken down by response (simple, finger choice and hand choice), validity (invalid, neutral and valid) and error type (pre-emptive response, delayed response of over 1000ms, or incorrect response in the choice conditions). A pre-emptive response was defined as one occurring either prior to, or within 50 ms of, stimulus onset.

A total of 4.4% (SD 3.5% across participants) of trials were rejected in the simple response condition. 3.0% had pre-emptive responses, 1.4% had responses of over 1000ms. These error trials were distributed proportionally across the validity conditions (Invalid: 1.3%, Neutral: 1.2%, Valid: 2.0%).

In the finger choice response condition a total of 5.6% (SD 3.7% across participants) of trials were rejected. 1.7% had pre-emptive responses, 0.9% had responses of over 1000ms, 3.0% had an incorrect response. These error trials were distributed proportionally across the validity conditions (Invalid: 2.0%, Neutral: 1.4%, Valid: 2.2%).

In the hand choice response condition a total of 4.5% (SD 2.3% across participants) of trials were rejected. 1.7% had pre-emptive responses, 0.9% had responses of over 1000ms, 1.9% had an incorrect response. These error trials were distributed proportionally across the validity conditions (Invalid: 1.5%, Neutral: 0.5%, Valid: 2.4%).
For the remaining trials, the two measures; ART and JRT, were recorded and averaged across target locations for each validity condition in each response condition. A two factor repeated measures ANOVA was conducted on each measure. The factors were response (simple, finger choice, hand choice) and validity (invalid, neutral, valid).

The mean ART (and SD) for each response and validity condition are shown in Table 7-1. Significant main effects of response ($F_{(2,26)} = 4.1, p = .03$) and validity ($F_{(2,26)} = 10.0, p = .001$) were found in the ART measure. There was no significant interaction between response and validity ($F_{(4,52)} = 1.7, p = .16$).

<table>
<thead>
<tr>
<th>Cue Validity</th>
<th>Simple</th>
<th>Finger Choice</th>
<th>Hand Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>376 (102)</td>
<td>418 (108)</td>
<td>409 (105)</td>
</tr>
<tr>
<td>Neutral</td>
<td>350 (88)</td>
<td>370 (70)</td>
<td>355 (56)</td>
</tr>
<tr>
<td>Valid</td>
<td>327 (83)</td>
<td>341 (51)</td>
<td>333 (56)</td>
</tr>
</tbody>
</table>

The significant main effects were investigated further using orthogonal planned contrasts. Within the main effect of response no significant difference was found between the simple response and finger and hand choice response conditions ($F_{(1,26)} = 2.3, p > .05$) or between the finger and hand choice response conditions ($F_{(1,26)} = 0.5, p > .05$). Within the main effect of validity no significant difference was found between the neutral cue and valid and invalid cue conditions ($F_{(1,26)} = 0.1, p > .05$). However, a
significant difference was found between the valid and invalid cue conditions \( (F_{(1,26)}=6.5, p< .05) \). On average the ART was 67ms faster for a valid cue (334ms) than for an invalid cue (401ms).

The JRT measure was then considered. The mean JRT for each response and validity condition is shown in Table 7-2. No significant main effect was found for response \( (F_{(2,26)}= 2.0, p= .16) \). However, a significant main effect was found for validity \( (F_{(2,26)}= 7.6, p= .002) \). There was no significant interaction between response and validity \( (F_{(4,52)}= 2.1, p= .10) \).

### Table 7-2 Judged Reaction Time (and SD) in ms for each response and validity condition

<table>
<thead>
<tr>
<th>Cue Validity</th>
<th>Response</th>
<th>Simple</th>
<th>Finger Choice</th>
<th>Hand Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td></td>
<td>425 (245)</td>
<td>516 (291)</td>
<td>489 (225)</td>
</tr>
<tr>
<td>Neutral</td>
<td></td>
<td>419 (272)</td>
<td>468 (287)</td>
<td>430 (212)</td>
</tr>
<tr>
<td>Valid</td>
<td></td>
<td>388 (263)</td>
<td>436 (226)</td>
<td>418 (220)</td>
</tr>
</tbody>
</table>

The significant main effect of validity was investigated further using planned contrasts. No significant difference was found between the neutral cue and valid and invalid cue conditions \( (F_{(1,26)}= 0.02, p> .05) \). However, a significant difference was again found between the valid and invalid cue conditions \( (F_{(1,26)}= 5.0, p< .05) \). On average the JRT was 63ms shorter for a valid cue (414ms) than for an invalid (477ms) cue.
Although the JRT is not numerically identical to the ART, the two RT measures show similar patterns (both qualitatively and numerically) across the validity conditions (see Figure 7.9). Most importantly, both show statistically significant differences between the valid and invalid cue conditions. This indicates that participants are aware that their response to an invalidly cued target is delayed relative to their response to a validly cued target.

**Figure 7.9** Actual and Judged Reaction Times (in ms) across validity conditions

- **Note:** Error Bars indicate Standard Error of the mean.

To further characterise the relationships between the conditions within each measure, a series of uncorrected t-tests was performed to establish whether a significant cost and benefit was present. Cost is demonstrated by a significant difference between the invalid and neutral conditions. Benefit is demonstrated by a significant difference between the valid and neutral conditions. A significant benefit was found for ART ($t_{(13)} = 5.8$, $p<$
.001) and JRT \((t_{(13)} = 3.2, p = .007)\). A significant cost was also found for both ART \((t_{(13)} = 2.4, p = .03)\) and JRT \((t_{(13)} = 2.2, p = .04)\).
Discussion

This study considered the extent to which the delayed Reaction Time (RT) in an attentional cueing task (Posner, 1978) enters into conscious awareness, with a view to establishing the locus of the effect.

Participants were required to make either simple or choice responses to pre-cued visual stimuli. The cue could either be valid, invalid or neutral. Previous research shows that in such a task RTs are fastest for a target that had been preceded by a valid cue, slower for a neutral cue and slowest for an invalid cue (Posner et al., 1978; Shore et al., 2001). There are a number of competing theories as to the locus of these effects (Posner et al., 1978; Shore et al., 2001; Pashler, 1998). Participants' experience of their RTs was measured using Verbal Time Estimation (VTE). This quantified the extent to which they were aware of the RT delays caused by the cues.

As expected, the cue was found to have a significant effect on the response time. On average the Actual Reaction Time (ART) was 67ms faster for a valid cue than for an invalid cue. This is in line with the findings of numerous other researchers (Posner et al., 1978; Shore et al., 2001).

This ART difference was also reflected in the Judged Reaction Time (JRT). Participants judged their RT to be significantly shorter (63ms) for a valid cue than for an invalid cue. It is therefore concluded that participants are aware that their RTs are delayed when responding to an invalidly rather than validly cued target. Although it would be
tempting to draw conclusions about the numerical similarity in the difference between ART and JRT (67ms and 63ms respectively) it would be inappropriate to do so. It cannot be assumed that a period judged to be 1ms is equal to 1ms in actual time. VTEs value lie in the relative differences between judgements rather than the absolute numerical difference.

The JRT results clearly show that participants do have motor awareness of their RTs. They are also able to use VTE to give a sensitive and accurate measure of their experience of their response time. It can therefore be concluded that VTE of RTs is an appropriate measure that is suitable for further use in the study of motor awareness.

These findings are compatible with previous research that suggests the attentional effect occurs after stimulus arrival (Johnson & Haggard, 2003). This suggests that the RT effect seen in these cueing tasks is not primarily caused by the Prior Entry effect. If it were then the effect could not be available to the participant for self report (see Figure 7.3). In addition, the effect can not occur after the participant has prepared the motor output (see Figure 7.4). As again, a delay at this stage would not be available to the participant for self report.

This still leaves a number of possibilities. The detection and response to the stimulus could be dissociable (Neumann, 1990). In this case, the delay could be occurring in the response stream, with no measurable effect on the detection stream. This would be compatible with other theories that argue for parallel processing within this task, (Pashler, 1998) as well as those that claim it occurs at the response selection stage (Miller, 1998). This theory suggests that the primary cause of these effects is the most
likely response being pre-prepared and inhibited prior to a new response being initiated if a cue is unexpectedly invalid (Miller, 1998).

However, in the data presented here the effect was also seen in the SRT task. Here the same response, and therefore the same motor output, is used for both valid and invalidly cued targets. This does not easily fit with the argument that a pre-prepared response is being rejected, as the same response is required for all targets. It may be therefore, that although the behavioural effects are the same (a delayed RT) there are different processes at work within SRT and CRT tasks, the locus of the effect could then be different in the two tasks.

It may be however, that this apparent contradiction is due to a flawed assumption about the nature of a movement. In an SRT task whilst the motor output may be quantitatively identical on all trials, at some higher level of psychological representation that output could be qualitatively different if made in response to different stimuli (see Figure 7.10). That is, 2 distinct action representations, corresponding to 2 stimuli, may compete to access the unique motor output. This would mean that in this case a stimulus-response pair is the basic unit of an ‘action’, rather than it being divided into its subcomponents, such as a motor plan, and motor output.
In this example, stimulus 1 is expected (e.g. on the basis of a directional cue) and so action 1 may be prepared ready to initiate the movement. However, if stimulus 2 were then presented (contrary to the cue), action 2 would be required instead. Although the actual movement is identical, for it to occur as a result of stimulus 2, action 1 must first be inhibited so that action 2 can become dominant. The critical feature of this model is that only one action plan at a time can access a given motor response, therefore the connection from a pre-activated plan must be inhibited before the alternative plan can access it.

This model would not only explain a difference between valid and invalidly cued targets, but also the differences between neutral and directional cues. It would allow a benefit to a validly cued target over a neutrally cued target as action 1 could be prepared in advance. It would also allow a cost to an invalidly cued target over a neutrally cued target as inhibiting action 1 would introduce an additional delay. An SRT within this
model may therefore be better described as a stimulus-action pair rather than stimulus-response.

Although this may appear to be inefficient in an SRT task, it could be practical in everyday life as it would prevent two stimuli simultaneously causing the same motor event. For example, if one wished to write, and both a pen and pencil were available there should be no attempt to grasp both objects at once. Therefore, it may be that Posner (1980) was correct when he described detecting as being equal to a stimulus-response pair. This could occur not because a response always follows detection at a constant rate, but because a given action can only be prepared in response to a single, specific stimulus.

This stimulus-action hypothesis would also be compatible with the findings of Henderson and Dittrich (1996) who reported that a simple response to two simultaneous stimuli was around 12 ms slower than when only 1 stimulus was present. The intuitive expectation would be that responses would be faster with additional stimulation. However, if the two stimuli caused two motorically identical but psychologically distinct responses to compete for access to a single motor output, then the final response could be delayed.

If this theory is correct then any attentional effect in any current cueing paradigm is likely to be subject to these response exclusivity effects. If however, it is incorrect, then a paradigm that removes or minimises response effects in a CRT should lead to a different pattern of results on motor awareness. Specifically, if the main RT delay is occurring at the response selection stage, then a paradigm which prevents a conflict at
that level should also prevent that delay. An example would be a task in which an action
plan is activated, but the pre-preparation of a specific motor response is prevented. One
such a task would be where the information provided by the spatial cue is orthogonal to
the response decision. Here, neither action plan would have a pre-prepared connection
to a specific motor output (see Figure 7.11).

Figure 7.11 Model of possible routes in an orthogonal choice response task

Having controlled for this effect, then any remaining delay would be attributable to
other causes. It is quite possible that there are multiple causes within the processing
stream that sum to a single RT delay. It may be that by removing any RT effect caused
by response selection then smaller effects such as Prior Entry could be become the
primary cause of the delay. In this case, the cause of the delay would no longer be
available to the participant and should no longer be reflected in their judgements of their
RTs. This issue is addressed in the next Chapter.
In Experiment 5 participants' experiences of traditional attentional cueing tasks were investigated. Spatially predictive cues were used in two Choice Response Tasks (CRT) and a Simple Response Task (SRT). Verbal Time Estimation (VTE) was used to give a quantifiable measure of the extent to which they were aware of their reaction time (RT). As expected (Posner et al., 1978; Shore et al., 2001; Pashler, 1998) it was found that participants responded faster to a target that followed a valid cue rather than an invalid cue. However, it was also found that participants were aware of this RT delay. That is, they also judged their RTs as being slower to invalidly rather than validly cued targets.

This result is interesting for a number of reasons. First, it demonstrates that participants have motor awareness of their RTs. This awareness is quantifiable and available for self report. It also shows that VTE is a sensitive and appropriate measure for investigating motor awareness. Second, it aids in establishing the locus of these attentional affects within the processing stream. As the effect entered awareness it was possible to rule out two potential loci; the primary effect cannot occur prior to stimulus arrival (Shore et al., 2001) nor after the motor command is prepared (Haggard et al., 1999).
This left the response selection stage (Miller, 1998; Pashler, 1998) as a likely possible locus. Alternatively, there may be two parallel processing streams, one devoted to motor responses to stimuli, and one to stimulus identification (Goodale & Milner, 1992; Neumann, 1990). The effect could then be occurring at the response selection stage (Miller, 1998; Pashler, 1998) within the response stream without impacting on the identification stream. If this is the case, then using a paradigm that reduces or removes effects at the response stage should result in a corresponding change in participants’ awareness.

One method of reducing effects of response selection is to use a SRT. As the same response is required for all targets in these tasks, there should be no need for an additional response selection stage. Therefore, if the RT effects of spatial attention arise only at the response selection stage, they should not be present in a SRT. However, it has long been known that spatial cueing effects are seen when using the SRT method (Posner, 1978; Posner et al., 1978; Posner, 1980; Johnson & Haggard, 2003). This finding was confirmed by the data in Experiment 5. In addition, it was shown that participants are also aware of this delay, just as they are with CRT. This suggests that either the effect that does not arise at the response selection stage, or that SRT is still subject to a response selection procedure, perhaps for the reasons outlined earlier in Figure 7.10.

To investigate this further an alternative method that reduces response selection effects is required. Such a method has been devised in relation to studies of Prior Entry using temporal order judgement tasks. Here the use of traditional CRT methods such as those used in Experiment 5 have been heavily criticised for being subject to response biases
In these studies rather than making a speeded RT to the target, participants are typically asked which of two stimuli appeared first. It is generally found that participants report that a stimulus in an attended processing stream occurs prior to a stimulus in an unattended processing stream. However, response bias would account for this result if, at times of uncertainty, participants tended to report that the target on the attended side appeared first. One method that has been devised to reduce this possible bias is orthogonal cueing (Drew, 1896; Shore et al., 2001; Spence et al., 2003).

In this paradigm the attentional cue given is orthogonal to the decision the participant is required to make. For example, the cue may be spatial (e.g. left/right) but the decision about the orientation of the stimulus (e.g. vertical/horizontal), and hence the response categories are orthogonal (Spence et al., 2003). Alternatively, both aspects may be spatial, but in opposite planes, with the cue being left/right and the decision being whether the target was up/down or front/back (Spence & Driver, 1994a). It is claimed that by doing this the opportunity for response bias is minimised (Shore et al., 2001). The theory behind this claim is that the cue does not give the participant any advance information as to which response will be required, therefore, they cannot pre-prepare that response.

If this claim is correct then using an orthogonal cueing paradigm should result in any effect of response pre-selection being reduced or removed. Therefore, any remaining RT difference must be due to other factors. In support of this theory it has been shown that the effect of the attentional cue decreases in orthogonal cueing tasks but does not disappear entirely (Spence & Driver, 1996). If such a task removes the portion of the RT delay caused by response preparation, what causes the remaining RT delay?
As discussed in the previous chapter, it has been argued that attended stimuli arrive prior to unattended stimuli. This effect is known as Prior Entry. Both previous research (Johnson & Haggard, 2003) and Experiment 5 have demonstrated that this theory does not explain the RT delay in traditional SRT and CRT attentional cueing tasks. However, if an orthogonal cueing paradigm removes the contribution of response pre-selection then any remaining delay could well be attributable to Prior Entry effects.

If this detection latency account of cueing effects is correct, then in an orthogonally cued task participants should not be aware of the delay in their RT. The full rationale behind this claim was discussed in the previous chapter (see Figure 7.3). However, to recap briefly, the Prior Entry effect is said to occur prior to stimulus arrival (Shore et al., 2001). As stimulus arrival is the earliest possible moment from which participants can judge their RT, any delay which occurs prior to this stage cannot be available for conscious self report. Therefore their judged reaction times (JRT) should not reflect the delay seen in their actual reaction times (ART).

However, if the JRT for valid and invalidly cued targets are still significantly different then once again, Prior Entry can be ruled out as the primary cause of the difference in the ART. In this case, what might be the cause of the difference? The effect could not be occurring after the motor command is prepared, as this would also fail to enter awareness, and it could not be due to response selection factors, as these are omitted by orthogonal cueing. Therefore, the locus would have to be elsewhere within the processing stream, after stimulus detection and before response selection.
One possible explanation would be that orthogonal cueing does not in fact remove effects caused at the response selection stage. If, as previously discussed, the basic unit of a movement is a stimulus-action pair, rather than a stimulus-response pair, then the cue could still trigger pre-preparation of an Action Plan, even if the precise motor output is not yet known (see Figure 8.1). That is, even if the precise response is still uncertain, action plans could be pre-prepared for stimuli on the side indicated by the cue, but inhibited for stimuli on the opposite side.

Figure 8.1 Schematic showing preparation of an Action Plan

If the cue then turned out to be invalid the participant would still have to inhibit the activated Action Plans, and select a new one, in this case either Action Plan 1 or 2. So if for example, target 1 was unexpectedly illuminated they would not be able to take advantage of the pre-preparation of the Action Plan for target 2, even though the motoric output required is identical.
It was therefore decided to investigate an orthogonally cued variant of the Posner attentional cueing paradigm. As Verbal Time Estimation has been shown to be a suitable measure participants will again be asked to judge their reaction times to the orthogonally cued stimuli. If the use of orthogonal cues removes the effects of response pre-preparation, then participants should no longer be aware of the delay in their RT.
Method

Participants

17 volunteers were each paid £7.50 to participate. The data from three participants were discarded, one due to equipment failure, one turned out to be left handed and one had a mean reaction time of over 1000ms. Of the remaining participants, 7 were male with a mean age of 26 (SD 3.18). All were non-psychologists and were naïve as to the purpose of the experiment. All were right handed with normal or corrected-to-normal eyesight by self report.

Apparatus

The experiment was conducted in a quiet, well lit room. Participants sat at a desk with their fingers resting comfortably on the appropriate keys on a keyboard. The stimuli were presented on a laptop computer screen using a custom programme. The laptop was arranged directly in front of the subject with the screen at a distance of 30cm. Participants responded by pressing the appropriate key on the keyboard.

Design

Participants completed 20 practice trials and 260 experimental trials. Experimental trials were presented in a random order, and practice trials were discarded from all analyses. There were four potential target positions; upper left, lower left, upper right, lower right. There were three cue types; directional left ('<'), directional right ('>') and neutral ('+'). There were three validity conditions; valid cue, (target appeared on the side
indicated by the cue), invalid cue, (target appeared on the opposite side to that indicated by the cue), or neutral cue, (no side was indicated). In all conditions the target could appear at any of the four locations, i.e. on either the left or right, and at either the top or bottom of the screen. The required response was an up/down decision, and therefore orthogonal to the left/right cue. (See Figure 8.2).

**Figure 8.2 Cue validity conditions**

<table>
<thead>
<tr>
<th>1: Valid Cue</th>
<th>2: Neutral Cue</th>
<th>3: Invalid Cue</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Note: the cue and target location are shown together here for clarity. They would not actually be simultaneously visible to the participant.

Each target position was presented on 15 trials with both invalid and neutral cues, making 60 trials for each of those validity conditions. Each target position was presented on 35 trials with a valid cue, making 140 trials in that validity condition and a
total of 260 trials. There was a break after every 25 trials, in addition, participants could stop the experiment and rest after any trial.

As with Experiment 5, it is probable that there will be an effect of target position but as this will be equally distributed across conditions and is not of interest in this experiment, all data will again be collapsed over target position. Two measures were investigated, Actual Reaction Time (ART) and Judged Reaction Time (JRT). A 3 level (valid cue, invalid cue, neutral cue) repeated measures ANOVA will be conducted on each measure. Significant main effects of cue validity will be investigated further using orthogonal planned contrasts comparing the neutral cue condition with valid and invalid cue conditions, and valid with invalid cue conditions.

**Procedure**

Participants were advised that a directional cue would be valid 80% of the time. They were instructed to keep their eyes fixated on the box in centre of the screen, but to direct their attention to the side indicated by the cue. When a neutral cue was presented they were advised to attend to both possible locations, as they were equally probable.

Participants responded with their right hand by pressing keys on a computer keyboard. They were asked to press ‘page up’ with their middle finger for an upper target and ‘page down’ with their index finger for a lower target, as quickly and accurately as possible. After making their response they were asked to verbally estimate their reaction times to the nearest ms. Participants were encouraged to be as accurate as possible and to avoid giving the same values repeatedly.
The remainder of the procedure was the same as for Experiment 5. A fixation box was displayed in the centre of the screen, and remained on throughout the trial. After a 1000ms delay a cue would appear within the box for 350ms. The cue would clear and a delay (randomised between 1000-1350ms) followed. A target would appear and remained on screen until the participant responded with a key press. The target would clear and the participant would give an estimation of their reaction time (see Figure 7.8)
Results

A number of trials were excluded from analyses. These are broken down by cue validity (invalid, neutral and valid) and error type (pre-emptive response, delayed response of over 1000ms, or incorrect response). A pre-emptive response was defined as one occurring either prior to, or within 50 ms of, stimulus onset.

A total of 7.0% (SD 5.1% across participants) of trials were rejected. 1.0% had pre-emptive responses, 1.5% had responses of over 1000ms, 4.5% had an incorrect response. These error trials were distributed across the validity conditions (invalid: 2.3%, neutral: 1.6%, valid: 3.1%).

For the remaining trials, ART and JRT were recorded and averaged across target locations for each validity condition (see Table 8-1). A repeated measures ANOVA was then conducted on each of the measures.

<table>
<thead>
<tr>
<th>Table 8-1 Mean Actual Reaction Times, (ART) and Judged Reaction Time (JRT) in ms (and SD) across validity conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cue Validity</strong></td>
</tr>
<tr>
<td>Invalid</td>
</tr>
<tr>
<td>Neutral</td>
</tr>
<tr>
<td>Valid</td>
</tr>
</tbody>
</table>

Significant main effects of validity were found for ART ($F_{(1,26)} = 20.96$, $p > .001$) and JRT ($F_{(1,26)} = 5.09$, $p = .014$).
The significant main effects were investigated further using planned contrasts. For the ART measure, no significant difference was found between the neutral cue and valid and invalid cue conditions \((F(1,26) = 3.7, p > .05)\). However, a significant difference was found between the valid and invalid cue conditions \((F(1,26) = 38.22, p < .001)\). On average the ART was 102ms faster for a valid cue (409ms) than for an invalid cue (511ms).

The JRT measure was then considered. No significant difference was found between the neutral cue and valid and invalid cue conditions \((F(1,26) = 2.34, p > .05)\). However, a significant difference was again found between the valid and invalid cue conditions \((F(1,26) = 7.79, p < .01)\). On average the JRT was 49ms shorter for a valid cue (402ms) than for an invalid cue (451ms).

As we saw in Experiment 5, the JRT is not numerically identical to the ART. However, once again, the two RT measures show similar patterns across the validity conditions (see Figure 8.3). Most importantly, both show statistically significant differences between the valid and invalid cue conditions. This indicates that even in an orthogonally cued task, participants are again aware that their response to an invalidly cued target is delayed relative to their response to a validly cued target.
To further characterise the relationships between the conditions within each measure, a series of uncorrected t-tests was performed to establish whether a significant cost and benefit was present. Cost is demonstrated by a significant difference between the invalid and neutral conditions. Benefit is demonstrated by a significant difference between the valid and neutral conditions. No significant benefit was found for ART ($t_{(13)} = 2.0, p = .06$) or JRT ($t_{(13)} = .01, p = .99$). However, a significant cost was found for both ART ($t_{(13)} = 3.8, p = .002$) and JRT ($t_{(13)} = 2.5, p = .02$).
Discussion

This study considered the extent to which the delayed Reaction Time (RT) effects in an attentional orthogonal cueing task (Spence et al., 2003; Spence & Driver, 1994a) enter into conscious awareness, with a view to further establishing the loci of these effects.

Participants were required to make an up/down decision regarding a target following a left/right endogenous cue. The cue could either be valid, invalid or neutral. Previous research shows that in such a task RTs are fastest for a target that had been preceded by a valid cue, slower for a neutral cue and slowest for an invalid cue (Spence et al., 2003; Spence & Driver, 1994a). This finding was replicated, on average the Actual Reaction Time (ART) was found to be 102ms faster for a valid cue than for an invalid cue.

Participants were also asked to give a Verbal Time Estimation (VTE) as a measure of their experience of their RT. On average their Judged Reaction Time (JRT) was also reported as being significantly shorter (49ms) for a valid cue rather than invalid cue. This demonstrates that participants were aware of the RT delay caused by the attentional cue.

These findings are compatible with those of Experiment 5. That is, the RT delay enters conscious awareness and participants are able to quantify it for use in self report through VTE. However, this is not compatible with some theories regarding the locus of the attentional effect.
As discussed previously, two potential loci can be ruled out if an RT effect is found to enter conscious awareness. It can not occur prior to stimulus arrival or after the motor command has been prepared. These are the earliest and latest possible points from which a participant can measure their own RT, and so events falling outside these bounds can not be available when making such judgements.

As Prior Entry is defined as occurring prior to stimulus arrival (Shore et al., 2001) it is once again ruled out as the primary cause of the RT delay in this experiment. Where then is the locus of the attentional effect in an orthogonal cueing task? The orthogonal cueing paradigm is designed to remove potential confounds with response preparation (Shore et al., 2001). Therefore, the attentional effect must arise prior to response selection. However, it may still be that orthogonal cueing reduces but does not remove response preparation.

It was proposed earlier that multiple potential Action Plans (AP) could be partially activated or inhibited according to the central cue. If this were occurring the benefit of a valid cue would be reduced, as the specific AP required could not be selected from those activated until the target was identified. However, the cost of a negative cue would remain similar. The partially activated APs would still have to be inhibited and the new AP activated. The benefit is defined as the difference between the RT to a valid cue compared with a neutral cue. The cost is the difference between the RT to an invalid cue compared with a neutral cue.

This pattern of smaller attentional benefits in orthogonal rather than non-orthogonal designs, together with a fixed attentional cost has previously been reported (Spence &
Driver, 1996). It would appear that the data in Experiment 6 also follows such a pattern. Here, there is a significant cost to ART but no significant benefit. In contrast, Experiment 5 used traditional spatial cueing, and found both a significant cost and benefit. It would therefore appear that use of orthogonal cues reduces the benefit but not the cost. Interestingly, these cost/benefit patterns are also reflected in the JRT in both experiments.

There was however, a small numerical benefit of the valid cue, which approached significance (p=.06) in the ART. This small benefit fails to enter awareness and could therefore be being caused by an effect such as Prior Entry, whilst the cost is due to a separate factor, such as response selection. Temporal awareness could be largely immune to the former effects, but very dependent on the latter. This idea would need considerable further research before it could be concluded with any certainty.

In summary, participants were found to be aware of the delay in their RT in an orthogonally cued CRT. This suggests that the primary effect of the cue arises at a response selection stage, despite previous assertions that such a paradigm reduces or removes such effects (Shore et al., 2001). These results are remarkably similar to those seen in Experiment 5, where traditional spatially informative cues were used in both SRT and CRT conditions.

This similarity is not unexpected as both experiments rely on very similar methods, and particularly on the use of endogenous cues. An endogenous cue is typically central in space and informative. That is, it *instructs* the participant which location is most likely to contain the target. In direct response to this the participant *intentionally* reorients
their covert attention to the location(s) indicated by the cue. As demonstrated in Experiments 5 and 6 this covert reorienting of attention leads to RTs to validly cued targets being enhanced, whilst RTs to invalidly cued targets are retarded. These experiments also showed that participants are aware of this effect and can report their RT through the use of VTE.

These results are interesting for a number of reasons. First it provides further evidence that participants are able to report their motor awareness of their RT. Second they have helped to localise the RT effect of attentional cues within the processing stream. However, they can also be considered beyond the confines of these tasks. In Experiment 1 it was also found that participants were able to report their motor awareness, though in that experiment it was through the use of movement reproduction. The results of that experiment differed from the present one, in that spatial awareness of motor corrections was found to be attenuated according to whether the movement was intended. Specifically, intentional movements (anti points) were found to enter awareness more fully than automated movements (pro points). The exception to this rule was erroneous movements.

As a result of these findings, (and also those of Experiments 2-4) it was proposed that an intentional component to an action may be essential for full motor awareness. The results of this Experiment and Experiment 5 are compatible with this suggestion as they both utilise endogenous, or intentional, cueing paradigms. However, if the assertion is correct, then if this task was repeated without the intentional aspect, then the participants’ awareness of their responses should be attenuated. To test this theory it
would be necessary to repeat this experiment using a non-intentional cueing paradigm.

Experiment 7 uses automatic, reflexive shifts of attention to achieve this.
9. Experiment 7: Awareness of response time in an exogenous orthogonal attentional cueing task

Introduction

In Experiments 5 and 6 participants’ experiences of attentional cueing tasks were investigated. Endogenous spatially predictive cues were used in a variety of response conditions (SRT, CRT, orthogonally cued CRT). Verbal Time Estimation (VTE) was used to give a quantifiable measure of the extent to which participants were aware of their reaction time (RT). As expected (Posner et al., 1978; Shore et al., 2001; Pashler, 1998) it was found that participants responded faster to a target that followed a valid cue than an invalid cue, even when the cue did not predict the exact motor response that would be required. However, it was also found that participants were aware of this RT delay. That is, they also judged their RTs as being slower to invalidly rather than validly cued targets. This effect was seen across all response conditions.

As participants were aware of the delay in their RT it was possible to rule out two potential loci for the attentional effect. The primary effect cannot have occurred prior to stimulus arrival (Shore et al., 2001) nor after the motor command is prepared (Haggard et al., 1999). It was therefore proposed that the effect arose at the response selection stage (Miller, 1998; Pashler, 1998), even in orthogonally cued tasks.
However, aside from these contributions to our understanding of the processes in these
tasks, it was also noted that there were parallels with aspects of Experiment 1. Notably,
participants were reporting motor awareness of an action that had a strong intentional
component. Following the findings of Experiment 1 (and to a lesser extent Experiments
2-4) it was proposed that an intentional component may be a pre-requisite for full motor
awareness. That is, an action that is fully automated may have little or reduced
corresponding motor awareness, whereas an action that has a large intentional
component will be more fully available for conscious self report.

The results of Experiments 5 and 6 are compatible with this hypothesis, but it would
also be predicted that in a similar task that has less or no intentional components, then
awareness should be attenuated. Although the precise tasks varied, the same basic
paradigm was used in Experiments 5 and 6; endogenous cueing. An endogenous cue is a
predictive cue that instructs the participant to covertly (i.e. without moving their head or
eyes) reorient their attention to the feature or location specified. However, there is a
second attentional cueing paradigm; exogenous cueing (Posner, 1980).

An exogenous cue varies from an endogenous cue in a number of ways. It is usually
peripheral, whereas endogenous cues tend to be central. It is not informative; in typical
experimental uses of these paradigms an exogenous cue is equally likely to be valid or
invalid whereas, an endogenous cue builds an expectancy as to the most probable
location or event. It is not under the participant’s immediate control; attention will be
automatically drawn to the exogenous cue whether or not the participant intends to do
so (Posner, 1980; Shore et al., 2001). That is, it is essentially an automated or reflexive
response.
Exogenous cueing also varies in that it is biphasic. A valid exogenous cue at a short stimulus onset will enhance a response to a target at that location. However, with longer intervals between the cue and stimulus, the response will be retarded. This cost is known as Inhibition of Return (IoR) (Posner & Cohen, 1984; Rafal, Calabresi, Brennan, & Sciolto, 1989). Whereas an endogenous cue is usually presented further in advance of the stimulus, in order to give the participant time to intentionally reorient their attention.

Finally, there is converging evidence that exogenous and endogenous mechanisms may have different underlying neural pathways (Briand, 1998; Posner & Peterson, 1990). Specifically, it is argued that exogenous orienting of attention involves subcortical pathways (Rafal, Henik, & Smith, 1991) while endogenous orienting does not.

However, for the purpose of this thesis, endogenous and exogenous cueing paradigms are sufficiently similar as to provide a useful test of the hypothesis that awareness requires an intentional component. Both utilise cues prior to targets. Both require a response to that target and both cause measurable effects on the RT. Additionally, with a suitably short period between cue and stimulus onset, it can be ensured that a valid exogenous cue will accelerate RT and an invalid one retard it. This is clearly comparable at a behavioural level with the effects of the endogenous cues used in Experiments 5 and 6.

If an intentional component is necessary for motor awareness, then participants should not be aware of delays in their RT caused by purely automatic or reflexive processes. If however, a delay caused by an automatic process does enter awareness then either the
exogenous cueing paradigm must have a greater intentional component that first
thought, or the initial assertion that intention is a pre-requisite for awareness must be
rejected.

It was therefore decided to investigate an exogenous orthogonally cued variant of the
Posner attentional cueing paradigm. As Verbal Time Estimation has been shown to be a
suitable measure, participants will again be asked to judge their reaction times. If
intention is a pre-requisite for conscious motor awareness, then participants should no
longer be aware of the delay in their RT.
Method

Participants
14 volunteers were each paid £7.50 to participate. All were non-psychologists and were naïve as to the purpose of the experiment. All were right handed with normal or corrected-to-normal eyesight by self report. 6 were male with a mean age of 26 (SD 6.13).

Apparatus
The experiment was conducted in a quiet, well lit room. Participants sat at a desk with their fingers resting comfortably on the appropriate keys on a keyboard. The stimuli were presented on a laptop computer screen using a custom programme. The laptop was arranged directly in front of the subject with the screen at a distance of 30cm. Participants responded by pressing the appropriate key on the keyboard.

Design
Participants completed 8 practice trials and 160 experimental trials. Experimental trials were presented in a random order, and practice trials were discarded from all analyses. There were four target positions; upper left, lower left, upper right, lower right (see Figure 8.2). Cues were presented peripherally as white rectangles covering both upper and lower target locations on one side. There were four cue conditions; both cues, no cue, valid cue or invalid cue (see Figure 9.1). In each cue condition the target could appear at any of the four locations, i.e. on either the left or right, and at either the top or
bottom of the screen. The required response was an up/down decision, and therefore orthogonal to the left/right cue.

**Figure 9.1 Cue validity conditions**

1: No Cue 2: Both Cues 3: Valid Cue 4: Invalid Cue

![Cue validity conditions diagram](image)

- potential target location  - response key  - peripheral cue
- target  - central fixation

**Note:** the cue(s) and target location are shown together here for clarity. They would not actually be simultaneously visible to the participant.

Each of the 4 target positions were presented on 10 trials in each of the 4 cue conditions, making 40 trials for each cue condition and a total of 160 trials. There was a short break after every 25 trials. In addition, participants could stop the experiment and rest after any trial.
As with Experiments 5 and 6, all data will be collapsed over target position. Two measures were investigated, Actual Reaction Time (ART) and Judged Reaction Time (JRT) using VTE. A 4 level (valid cue, invalid cue, no cue and both cues) repeated measures ANOVA will be conducted on each measure. Significant main effects of cue validity will be investigated further using three planned contrasts comparing the no and both cue conditions with valid and invalid cue conditions, valid with invalid cue conditions and both with no cue conditions.

**Physiological Measurements**

Eye movements were monitored by recording EOG, unfiltered at 1000 Hz. Disposable Ag/AgCl surface electrodes (ARBO Inc) were used. They were positioned on either temple. The signals were recorded on a computer for later analysis. The standard deviation of the EOG signal during a baseline period of 40 ms prior to cue onset was calculated to estimate noise in the EOG signal. If the EOG activity exceeded 2 times this level during a trial, the data for that trial was rejected.

**Procedure**

Participants were advised that a ‘distracter’ would be presented on 75% of trials. They were instructed to keep their eyes fixated on the box in centre of the screen, and to ignore the distracter as it was random and uninformative and would not help them to predict the target location. Participants were asked to respond to the target by pressing ‘page up’ with their middle finger for an upper target and ‘page down’ with their index finger for a lower target, as quickly and accurately as possible. After making their response they were asked to estimate their reaction times to the nearest ms. Participants
were encouraged to be as accurate as possible and to avoid giving the same value repeatedly.

A fixation box was displayed in the centre of the screen, and remained on throughout the trial. After a 1000ms delay a central cue (‘+’) would appear within the box, again this remained on throughout the rest of the trial. A delay (randomised between 100-200ms) followed. In a cue condition a peripheral cue (or cues) would then appear for 50ms. The peripheral cue(s) would clear and following a further delay (randomised between 50-150ms) a target would appear and remained on screen until the participant responded with a key press. The target would clear and the participant would give an estimation of their reaction time (see Figure 9.2).

**Figure 9.2 Schematic showing time course of a trial**
Results

A number of trials were excluded from analyses. These are broken down by cue validity (invalid, neutral and valid) and error type (pre-emptive response, delayed response of over 1000ms, incorrect response, or eye movement detected). A pre-emptive response was defined as one occurring either prior to, or within 50 ms of, stimulus onset.

A total of 8.9% (SD 10.2% across participants) of trials were rejected. 0.1% had pre-emptive responses, 5.3% had responses of over 1000ms, 0.5% had an incorrect response, 2.9% had detectable eye movements. These error trials were distributed across the validity conditions (both cues: 2.0%, no cue: 1.9%, invalid cue: 2.6%, valid: 2.3%).

For the remaining trials, ART and JRT were recorded and averaged across target locations for each validity condition. A repeated measures ANOVA was then conducted on each of the measures.

A significant main effect of validity was found for ART (F (1,26)= 24.99, p< .001). No significant main effect of validity was found for JRT (F (1,26)= 2.09, p= .12). The significant main effect in the ART measure was investigated further using planned contrasts. A significant difference was found between both cues and no cue and valid and invalid cue conditions (F (1,26)= 22.52, p< .001). A significant difference was also found between the both cues and no cue conditions (F (1,26)= 37.39, p< .001) on average the ART was 45ms faster for both cues (599ms) than for no cue (644ms). More importantly, a significant difference was also found between the valid and invalid cue
conditions (F(1,26) = 15.02, p < .001). On average the ART was 29ms faster for a valid cue (582ms) than for an invalid cue (611ms).

Table 9-1 Mean Actual Reaction Times (ART) and Judged Reaction Time (JRT) in ms (and SD) across validity conditions

<table>
<thead>
<tr>
<th>Cue Validity</th>
<th>ART</th>
<th>JRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>611 (72)</td>
<td>409 (182)</td>
</tr>
<tr>
<td>Both</td>
<td>599 (64)</td>
<td>391 (175)</td>
</tr>
<tr>
<td>Valid</td>
<td>582 (61)</td>
<td>395 (183)</td>
</tr>
<tr>
<td>None</td>
<td>644 (76)</td>
<td>392 (170)</td>
</tr>
</tbody>
</table>

Unlike the results in Experiments 5 and 6, the two RT measures do not show similar patterns across the 3 most comparable validity conditions (invalid, both, valid, see Figure 9.3). Most importantly, participants show a statistically significant delay in their ART when responding to an invalidly cued target rather than a validly cued target, but this difference is not statistically significant in their JRT. This indicates that in an orthogonally cued exogenous cue task, participants are essentially unaware that their response to an invalidly cued target is delayed.
Although there was no significant main effect of validity in the JRT there is a numerical difference of 14ms between the mean JRT for the valid and invalid cue conditions, in order to be able to claim that participants were not aware of their delayed reaction times it is critical to ensure that a Type II error is not made at this point. Therefore, the planned contrast of valid cue and invalid cue conditions was conducted and no significant difference was found between the JRT in the valid and invalid cue conditions \( (F(1,26) = 2.89, p > .05) \). Further, when the individual results of the participants are considered, it is clear there is no consistent difference between the JRT for the two cue types (see Figure 9.4).
To further characterise the relationships between the experimental conditions within each measure. A series of uncorrected t-tests was performed to establish whether a significant cost and benefit was present. Cost is demonstrated by a significant difference between the invalid and both cues conditions. Benefit is demonstrated by a significant difference between the valid and both cues conditions. No significant cost was found for ART ($t_{(13)} = -1.9$, $p = .08$) or JRT ($t_{(13)} = -2.0$, $p = .06$). No significant benefit was found for JRT ($t_{(13)} = -.46$, $p = .65$), however a significant benefit was found for the ART ($t_{(13)} = 2.2$, $p = .04$).

Figure 9.4 Distribution of difference between invalid and valid JRT

It should also be noted that the significant difference in the ART between the both cues and no cues conditions also failed to be reflected by the JRT (see Figure 9.5).
Figure 9.5 ART and JRT in both and no cue conditions
Discussion

This study considered the extent to which the delayed Reaction Time (RT) effects in an exogenous cueing task (Spence & Driver, 1994b; Spence & Driver, 1994a) enter into conscious awareness. The aim was to investigate whether intention is a pre-requisite for motor awareness.

Participants were required to make an up/down decision regarding a target following an exogenous cue. The cues were brief and were presented 50-150ms prior to the target. The cue presentation could be valid, invalid, both or neither. The cues were not informative; a rightward target was equally likely to follow a right or left cue. Participants were therefore advised to consider them to be ‘distracters’ and to ignore them. Previous research shows that in such a task RTs are fastest for a target that had been preceded by a valid cue, slower for a neutral cue and slowest for an invalid cue (Spence et al., 2003; Spence & Driver, 1994a) and that the presentation of any cue will have a general alerting effect compared with no cue (Enns & Richards, 1997). These finding were replicated. On average the Actual Reaction Time (ART) was found to be 102ms faster for a valid cue than for an invalid cue, whilst having no cue led to the slowest RT. A significant difference was also found between the two ‘neutral’ cue conditions. On average the ART to a target that was preceded by both cues was 46ms faster than for one with no cue. This latter difference reflects the general alerting effects of a cue (Enns & Richards, 1997) rather than any benefit from spatially relevant information.
Participants were also asked to give a Verbal Time Estimation (VTE) as a measure of their experience of their RT. No significant difference was found between the average Judged Reaction Time (JRT) for validly cued rather than invalidly cued targets. A small difference of 14ms was observed, but this was neither significant, nor consistent across participants. It appeared to be due to two outlying participants. There was also no significant difference between the JRT for targets preceded by both cues compared to those with no cue. This demonstrates that participants were not aware of the RT effects caused by the exogenous cues.

These findings are quite different from those in Experiments 5 and 6 found with endogenous cues. In those experiments participants were found to be aware of the RT effects caused by the attentional cues. This pattern of findings was predicted by the results of the earlier experiments in this thesis, but primarily by Experiment 1. It was proposed that a strong intentional component is a pre-requisite for motor awareness. Experiments 5 and 6 used endogenous cues, these require the participant to intentionally reorient their attention to the location indicated by the cue. However, the present experiment used exogenous cues which reflexively or automatically reorient attention, without any intention on the part of the participant. Indeed, participants are instructed to ignore the cues as they are not predictive of target location. This pattern of results across Experiments 5, 6 and 7 therefore supports the suggestion that an intentional component is necessary for conscious motor awareness.

It also raises questions about the locus of the RT effects in exogenous cueing tasks. It may be that the locus is identical to those in endogenous tasks, but that the lack of intention means they fail to reach conscious motor awareness. However, it may be that
they have either entirely or partially different underlying mechanisms. This latter claim has received some support from recent studies (Briand, 1998; Posner & Peterson, 1990).

As discussed in Chapter Seven, an effect that enters awareness cannot occur prior to detection nor after the motor response has been prepared. However, an effect that fails to enter awareness could fall outside of these boundaries. Alternatively, it could fall within them, but occur in a processing stream that is not available to conscious report. Finally, it may simply be that the effects are available to consciousness, but are only accessed under the appropriate conditions, such as when an intentional component is present.

In this connection, the present results can usefully be compared with an experiment by Shore et al (2001). Those authors used an orthogonal cueing design to reduce the effect of response bias on temporal order judgements in a Prior Entry paradigm. They found very different effects with endogenous and exogenous cues. After the removal of response biases the Prior Entry effect was found to be reduced to just 17ms for the endogenous cue condition, but was 61ms for the exogenous cue condition. It could be that the RT effect of an exogenous cue fails to enter awareness because it occurs prior to stimulus arrival (Shore et al., 2001). That is, exogenous attentional effects on RT may be due to the Prior Entry effect.

Finally, it could be argued that the present result is in fact trivial. The exogenous attentional effect may fail to enter awareness simply because the effects of exogenous cues are smaller than those for endogenous cues and so are too small for the participant to notice. However, this is unlikely to be a full explanation as the general alerting effect
of the cue (calculated as the difference between the RTs when no cue was presented and when both were present) also failed to enter awareness. The difference between no cue and both cues was 45ms, a difference comparable with those found in Experiments 5 and 6 that did enter awareness.

Additional research is therefore needed in order to establish the loci of the RT effects caused by exogenous cues. Specifically, it would be interesting to run an experiment based on the Libet (1985) paradigm, as used by Johnson and Haggard (2003), using exogenous cues as opposed to the endogenous cues used in that study. If the exogenous attentional effect on RT is due to Prior Entry participants should judge the target onset to occur later following an invalid rather than valid exogenous cue. In addition, it would be possible to take advantage of the biphasic nature of exogenous cueing and use the same paradigm to investigate Inhibition of Return (IOR). If IOR is a reversal of the original effect, then participants would now report earlier arrival times for the invalidly cued target. However, if it was caused by some other mechanism that arose later in the processing stream, the arrival times should be reported as equal.
10. Summary and conclusions

This thesis has investigated various aspects of motor awareness. Two primary methods were used; the first was movement reproduction, which gave a measure of the spatial details of participants' awareness. This was a kinematic approach and was essentially a new method of reporting motor awareness. The second was temporal judgements, which gave a measure of participants' awareness of the duration of their movements. This was essentially a cognitive approach, as participants gave verbal reports about their subjective experiences. Both methods were found to be sensitive and appropriate measures for the investigation of motor awareness.

Movement reproduction was used in Experiments 1, 2 and 3. In Experiment 1 the relationship between motor performance and motor awareness was investigated, with specific emphasis on the role of intention. A variety of pointing movements were considered. Participants were asked to report their motor awareness by reproducing the movement they had just made. The critical finding of this experiment was that under some conditions motor awareness could dissociate from motor performance. Participants showed attenuated awareness in automated movements, but more accurate, and even exaggerated, awareness of intentional movements. The exception to this was anti point errors. These automatic, but erroneous movements entered awareness as accurately as intentional movements did.

The mechanisms that cause motor awareness appear to be quite different for intentional and automated movements. Awareness of intentional movements is pre-emptive and
forward looking. Error awareness however is retrospective, a reconstruction of the event once the error has been detected. Yet the similarity of the psychophysical measures of participants’ experiences of these movements was striking. Could there be a common neural mechanism that produces similar conscious experiences, and therefore similar psychophysical values, underlying the two different systems? Executive function theorists have proposed a supervisory attentional system (SAS) that is involved in both planning and monitoring actions (Shallice, 1991). Such a system would explain the data presented here, that intention plays a major role in awareness. It would also account for the same SAS being triggered by erroneous automated movements. This would give rise to two systems accessing conscious experience in very different ways, whilst generating similar conscious experiences.

Experiment 2 again used movement repetition. However, this experiment primarily looked at the relationship between motor awareness and perceptual awareness in the saccadic suppression paradigm. It was found that participants could reproduce the correction in their movement even when they were unaware of the target shift that caused it. This demonstrates that motor and perceptual awareness can dissociate.

Experiment 3 attempted to build on this finding. A previous study by Desmurget et al (1999) had shown that by stimulating the PPC with TMS, online corrections could be disrupted in the saccadic suppression paradigm. Experiment 3 aimed to investigate what would happen to motor awareness in these circumstances. This study replicated the finding of Experiment 2; participants were again able to reproduce the deviations in their trajectories, whilst remaining unaware of the target shift that caused them.
Unfortunately, the basic effect, disrupting the correction with TMS, was not replicated. Therefore, it was not possible to investigate the original hypothesis further.

The combined data from these experiments led to a number of conclusions. It was established that a distinct and reportable form of motor awareness exists, and that it can dissociate from both perceptual awareness and motor performance. It was also proposed that intention plays a critical role in the extent to which a participant has motor awareness of their movement. Finally, it was noted that motor awareness itself appears to either take multiple forms, or fall along a continuum. It is possible to have motor awareness of a deviation in a movement, but not to be able to extrapolate perceptual data from that. As such, it would seem that motor awareness can be encapsulated, and is not necessarily available to any 'global' form of consciousness. There is a tendency in the perceptual literature to suggest that consciousness is unitary. The present data suggests that is can dissociate into at least two relatively independent parts. It was proposed that these multiple forms of awareness may have differential access to a global form of consciousness, such as the global workspace proposed by Baars (1983). This would account for both the intuitive feeling of a unitary consciousness in daily life, and the sub divisions of awareness that can be seen experimentally.

In order to more fully characterise the nature of motor awareness it was decided to investigate other types of movements using different measures. In particular, the role of intention was explored more fully. In this second part of the thesis two types of temporal judgements were used. In Experiment 4 a variant of temporal discrimination was used to measure awareness in saccades. This method has previously been shown to be a sensitive measure of the Chronostasis effect that is seen during saccades under
certain conditions (Yarrow et al., 2001). Saccades can be manipulated along similar dimensions to those used in the pointing task of Experiment 1. As in pointing tasks, there are different ‘classes’ of saccades, these include more automated pro saccades towards a target, and slower, intentional anti saccades away from a target. The intentional aspect is seen in the pre saccade delay and the automated component in the saccade duration. The extent to which the delayed response in the anti saccade task was reflected in the Chronostasis effect could then be considered. A dissociation was found in the extent to which the automated and intentional components were reflected in the Chronostasis effect. That is, the pre saccade delay seen in anti saccade trials did not lead to a greater Chronostasis effect. Instead, the effect remained the same as in pro saccades and reflected only the automated component (saccadic duration), which was the same for all saccade types. This finding is compatible with the pointing data from Experiments 1, 2 and 3, but especially with Experiment 1. The intentional, planning component of the anti saccade task was not subject to the Chronostasis illusion, whereas the automated, motor component was. Specifically, the duration of the motor component was recategorised as a period of perceptual awareness. Whereas, the pre saccade planning was not recategorised in this way, instead the duration of that period was respected by perceptual awareness.

Experiments 5, 6 and 7 aimed to establish the extent to which the findings of Experiments 1, 2, 3 and 4 could be further generalised across different measures and different movements. In addition, they aimed to consider the extent to which attentional effects enter motor awareness and to help identify the loci of those effects. Participants’ awareness of the duration of their reaction times (RT) was investigated using a different temporal measure; verbal time estimation (VTE).
Experiment 5 incorporated two traditional endogenous cueing paradigms; Simple Response Task (SRT) and Choice Response Task (CRT). In these tasks a predictive, intentional cue affects RT to a target that follows it. A valid cue that correctly indicates the target’s future location speeds RT, whilst an invalid cue slows it. It was found that participants were aware of the effects the attentional cues had on their RTs.

The cause of the RT delay in endogenous cueing tasks has been much debated. The CRT paradigm used in Experiment 5 has been criticised for being potentially due to response bias rather than pure attentional effects (Pashler, 1998). Previous researchers designed an orthogonal cueing task to reduce this problem (Drew, 1896; Shore et al., 2001; Spence et al., 2003). Experiment 6 repeated the previous VTE task with this orthogonal endogenous cueing design. It was proposed that if the participants’ awareness of the effects seen in Experiment 5 were response based, then after reducing any response effect their awareness should also decrease. However, it was found that even with orthogonal endogenous cues, participants were still aware of the delay in their RT.

Finally, Experiment 7 returned to the proposal that intention plays a major role in awareness. The data from Experiments 1 and 4 suggested that participants are primarily aware of intentional movements, whilst awareness of automated movements is attenuated. The paradigms used in Experiments 5 and 6 both involved endogenous cues. Endogenous cues are predictive and intentional. That is, a participant must deliberately and intentionally direct their attention to the position indicated by the cue. Therefore, the finding that participants are aware of the delays in their RTs in these cueing tasks
with a strong intentional component, is compatible with the results of Experiments 1 and 4. Experiment 7 aimed to test this hypothesis by removing the intentional component and investigating whether participants’ awareness remained. An orthogonal design similar to that used in Experiment 6 was used, however, exogenous cues were used instead of endogenous cues. Exogenous cues draw attention to their location reflexively and automatically. At short latencies the effect is much the same as with an endogenous cue, RT are faster when the cue is valid and correctly indicates the future location of the target and slower when it is invalid. This effect occurs regardless of whether the participant intends to direct their attention to that location. In Experiment 7 participants were explicitly instructed to ignore the exogenous cues, which were entirely random and non predictive. As a result, the attentional effects are purely automated, with no intentional component. It was found that under these conditions participants were no longer aware of the delay in their RT. It was concluded that this result was compatible with the hypothesis that intention plays a major role in motor awareness.

If we return to the model proposed in Chapter 4, the relationships between these studies can be seen more clearly (see Figure 10.1).
The 'intention' input to motor awareness was investigated in Experiments 1, 5 and 6. Experiment 1 also considered input from the motor system, in the form of goal achievement and intentional corrections. Automated movements were investigated in Experiments 1, 2, 3 and 4. Experiment 3 attempted to interrupt the automated corrections, possibly mediated by the PPC. Experiments 2, 3 and 4 investigated the role of perceptual awareness whilst Experiments 5, 6 and 7 considered attentional effects.

The results of all the studies are compatible. Experiments 2 and 3 confirm that motor awareness is at least partly independent of visual perception. Experiments 1, 4, 5 and 6 confirm that intention plays a major role in awareness. Whilst Experiments 1, 2, 3, 4
and 7 confirmed that motor awareness does not have full access to automated movements. This pattern of findings also provides further support for the model presented in Figure 10.1. In particular, they suggest that there are several, dissociable processing streams, with motor awareness receiving multiple inputs in a stream that is independent of perceptual awareness.

In terms of the original aims of this thesis, 2 measures of motor awareness were developed; movement reproduction and temporal judgements. Both were found to be sensitive and appropriate measures for investigating motor awareness. Motor awareness was characterised as being available for report, but not necessarily available to global consciousness. It was established that motor awareness is not a property of specific motoric output, it was instead proposed that intention plays a critical role in the extent to which information about a movement will enter awareness.

Clearly this is an area that requires considerable further research as this pattern of findings raises as many questions as it answers. Do these characteristics of motor awareness hold true for all types and classes of movements? Are there several discrete forms of motor awareness, or does it fall along a continuum? When patients have clinical disorders of movement, such as a failure to make automated corrections, what pattern does their awareness show? When patients have clinical disorders of motor awareness, such as anarchic hand syndrome, what pattern does their awareness show? Are these disorders of awareness simply exaggerated aspects of the normal motor system?
It would also be of interest to try and dissociate the various aspects of an action further. The relationship between failed automated corrections and motor awareness requires further consideration. It may also be possible to further tease apart the relationship between intention and attention, and the affect these have on motor awareness.
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Appendices

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Incorporating data from Experiment 4

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The data from this paper is not presented here. It was previously presented towards a MSc at UCL. However, it provides the basis and experimental rationale for Experiments 5, 6 and 7.
Appendix A


Based on data from Experiment 1
Abstract | Subjects’ awareness of motor corrections was investigated in a double-step pointing task. An unpredictable lateral target displacement of 10 cm, either left or right, during an ongoing reaching movement led to corrections of the trajectory. Subjects were required either to follow the target (pointing) or move in the opposite direction (anti-pointing). The target jump elicited rapid corrections to the movement in the direction of the target shift. These corrections were in some sense involuntary as they sometimes occurred in anti-point trials, when subjects were instructed to correct in the opposite direction to the target jump. The instructed correction away from the target in anti-point trials occurred later than the correction towards the target in standard pointing. Subjects were also asked to report their awareness of the motor correction they had just made by immediately reproducing each movement. In normal pointing, subjects showed reduced and delayed awareness, suggesting that the corrections were at least partly automatic. Anti-pointing corrections did not show this dissociation between performance and awareness. We suggest that anti-point corrections, but not standard pointing corrections, involve an additional supervisory system. This system is characterised by its slow operation and its access to conscious awareness.

Keywords | Motor control · Visuomotor adjustment · Double step corrections · Awareness of action · Conscious experience

Introduction
Previous studies have shown that subjects are able to make fast corrections to an ongoing movement (Day and Lyon 2000; Paulignan et al. 1991). The result is a double-step movement, that is, an initial movement towards the first target location followed by a fast online correction to the final location. The delay of these corrections is believed to be as early as 100–150 ms (Paulignan et al. 1991; Prablanc and Martin 1992).

Pélisson et al. (1986) showed that subjects could correct their movement to a new location without being aware that the target had shifted. Here, subjects fixated on a central point then made a saccade to a peripheral target. On some trials the peripheral target moved during this saccade. The resulting retinal error was compensated for by a second corrective saccade and subjects ascribed it to saccadic undershoot rather than a target shift. However, subjects were equally efficient at pointing to the final target location as when there had been no target shift. The authors concluded that these corrections occurred without entering consciousness.

Day and Lyon (2000) investigated subjects’ ability to control the online corrections. Here, rather than a covert shift of a peripheral target during a saccade, there was an overt shift of a central target 25 ms after movement onset. Subjects had to move either with or against the target. That is, subjects either followed the target to its new location (pointing condition) or they moved in the opposite direction (anti-pointing condition). They found that the intention to move away from the target in the anti-point condition suppressed the fast corrections in 24% of trials. In addition, in those anti-point trials where an early correction was present, it was almost always in the wrong direction. Day and Lyon concluded that the early response was automated and could not be reversed.

A similar result was reported by Pisella et al. (2000). Here a target colour change, rather than an anti-point, was used to induce an intentional response. Again they found that subjects made erroneous automated corrections to a target displacement. These errors were not seen in
response to a target colour change, suggesting a dissociation between these two mechanisms of movement correction.

Castiello et al. (1991) attempted to investigate subjects' awareness of their early corrections. They asked the subjects to make a vocal response, 'Tah!', as soon as they were aware that the target had moved. Castiello et al. found that the verbal responses occurred some 300 ms after the movement correction began. They concluded that subjects' conscious awareness of the target shift did not occur until considerable additional processing had been concluded.

These studies therefore suggest that early corrections to an ongoing movement are automated and subject to a delay before entering awareness. They cannot be reversed and can only partially be suppressed by a subject's deliberate intention. They also demonstrate a dissociation between perceptual awareness (i.e. awareness of the target shift) and motor performance. However, none of these studies have directly considered subjects' motor awareness of these corrections, that is, subjects' reportable knowledge about their own motoric output. Humans are consciously aware of the initiation of physical responses; we are able to report that we are moving or that we have moved. In addition, we receive proprioceptive feedback during a movement and, where appropriate, information about goal achievement afterwards. All of this suggests that there is some form of motor awareness that encompasses more than just perceptual awareness of a stimulus. Yet Pélisson et al. (1986) and Castiello et al. (1991) assumed that subjects' perceptual awareness (their explicit knowledge of a target shift) is equivalent or identical to their motor awareness (their knowledge of their physical response).

This is not necessarily the case. If subjects have other forms of awareness, specifically motor awareness, available to them, they may be able to report their knowledge of their physical response in the absence of perceptual awareness. In addition, the two classes of movement (early, automated and late, intentional) reported by Day and Lyon (2000) may be underpinned by different motor systems (Frith and Done 1986). As such, it may be that subjects have a differential motor awareness of their responses.

Therefore, a number of questions remain:

1. To what extent are subjects aware of the deviations in their trajectories on perturbation trials?
2. How does this awareness differ across response types? (i.e. automated movements, intentional movements and erroneous automated movements).

There is not, at present, an accepted method of measuring motor awareness. However, the agreed concept requires subjects to report the kinematic details of the movements they made to achieve their goal. Therefore, immediately after each trial subjects were asked to reproduce the entire path of the movement they had just made. Motor performance and motor awareness were then compared in pointing and anti-pointing movements.

### Materials and methods

#### Subjects

Thirteen volunteers were recruited from an opportunity sample of UCL students. They were paid £5 an hour to participate. One subject was excluded as they failed to make movement corrections. Of the remaining participants, six were female and six were male, all were right-handed and they had normal or corrected to normal vision by self-report. Their ages ranged from 22 to 36 years (mean 27.75 years).

#### Apparatus

The experiment was conducted in a small, dark testing booth. Subjects sat at a desk with their right hand resting comfortably on a start button. An electromagnetic Polhemus Fastrak marker was taped over the nail of the right index finger. A black mounting board was positioned vertically in front of the subject, 40 cm from the response button. Five red LEDs were arranged on a board directly in front of the subject. The central LED was 40 cm in front of the start button; the other LEDs were aligned horizontally, 10 cm and 20 cm either side of the centre (see Fig. 1). All the LEDs were 3 cm above the desk. On 33% of trials 25 ms after the start button was released, the central LED was extinguished and either a left or right LED was immediately illuminated. The two end LEDs were dummies that never illuminated. They were used only in additional conditions involving amplitude change, where subjects pointed beyond the target. The results of these conditions will be reported in a later paper.

#### Design

Trials were presented in blocks. A practice block of 12 trials was completed at the start of each of the two experimental blocks. The two blocked conditions were point and anti-point. The presentation order of the experimental blocks was counterbalanced across subjects. Each experimental block consisted of 120 trials. In 80 trials, the central LED remained on and did not jump; in 20 it jumped left and in 20 it jumped right. The order of presentation was randomised both within blocks and across subjects. Each trial consisted of one initial movement – reproduced movement pair.

![Fig. 1 Experimental setup](image-url)
Subjects were told that each trial had two components. The first would be to reach out and touch the illuminated LED as quickly and accurately as possible before returning to the response button. The second would be to immediately repeat the spatial path of the movement they had just made as accurately as possible. They were instructed that the emphasis was on spatial rather than temporal reproduction. Subjects were then told that in one-third of trials the LED would jump after they had begun to move. The apparatus was demonstrated and subjects were shown how the central LED could jump to one side or the other. In all conditions, subjects were told that if the LED did not jump they should simply continue their movement to the original position and then repeat their path. If the target jumped the instructions varied according to the blocked condition (see Fig. 1).

Procedure

1. Point. 'If the LED jumps, please follow it to its new location. Please try to correct your movement as quickly and accurately as possible.'

2. Anti-point. 'Please move in the opposite direction to the LED. Please try to correct your movement as quickly and accurately as possible.'

After both initial and reproduced trials they returned to the start button and the LED remained illuminated at its final location (Fig. 2). Movements were tracked in the X and Y dimensions at 120 Hz.

Measurement

Spatial resampling

In any one trial, the initial and reproduced paths could be of different temporal durations. To ensure comparability, they were first resampled spatially. That is, the X value (lateral deviation) was taken at 1-cm values along the Y-axis. These X values were then replotted against Y (distance travelled) rather than against time. The resulting paths were then foreshortened at 27 cm to remove the effects of averaging across reach lengths, which could vary slightly due to changes in initial and final hand position. They were then plotted backwards after being aligned at the peak Y value, which corresponded to the location of the target LED (as described in 'Materials and methods'). This meant that a short section was lost at the start of each movement. This gave a spatial rather than temporal path (Haggard and Richardson 1996).

Fig. 2 Schematic representation of experimental events across time in a perturbation trial

Estimation error

The initial and reproduced spatial paths were then compared. Estimation errors were calculated as the difference between the two paths (Fig. 3). The x positions of the reproduced path were subtracted from those of the initial path at 1-cm intervals along the spatially resampled trajectory. A negative value indicated an underestimation, where the subject was unaware of the extent of their movement or the speed of their correction. A positive value indicated an overestimation, where the subject was hyperaware of the deviation in their movement. That is, their awareness indicated a correction larger than they actually made. The values of the two types of estimation error were then integrated along the length of the trajectory. This resulted in two estimation errors, that is an underestimation and an overestimation, for each initial-reproduced path pair.

Latency calculations

On trials when the LED jumped (perturbation trials), the latency of the correction in the initial movement was calculated. However, as the initial and reproduced paths ran over different time courses, an intermediate spatial calculation was required to infer from the reproduced trials the latency at which subjects became aware of the correction in the initial movement. Figure 4 shows the initial and reproduced movement for a median trial in the Point condition. The initial latency of this trial was 341.6 ms and the reproduced latency was 504.6 ms. These figures were reached as follows:

First, the simple latency of the initial correction was calculated. The time when the LED jumped was taken as time 0 (A). The correction was defined as having occurred when the subject had moved 2 cm laterally, in the appropriate direction (position 0+2, B). Note that the appropriate direction is towards the target for pointing, but away from the target for anti-pointing. The time between the LED jumping (time 0) and this point was taken as the latency of the initial movement (initial latency).

These values were used to estimate latency of awareness using the reproduced movement. The X value used to detect correction in the initial movement (position 0+2, B) was found in the reproduced path (C). Since the reproduced movements did not share a common time course with initial movements, the latency of this point (C) is not interpretable. However, the spatial paths of initial and reproduced movements are related. Therefore, the spatial position of the hand at C can be interpreted. Therefore, the Y value at this point was calculated (D). This Y value was used to relate the reproduced path back to the initial path, and to find its corresponding point in the initial movement (E). The time at this point was then taken as the latency of the reproduced movement (reproduced latency). Note that the reproduced latency is not the time at which the reproduced movement deviated, but the time at which the initial movement had reached the Y position at which subjects reproduced a correction.

The difference between the initial and reproduced latencies was defined as the awareness delay, with a positive value indicating that the correction occurred later in the reproduced trial than in the initial trial. This method was used to calculate the latencies for both point and anti-point trials. In addition, it was used to establish whether
and when an anti-point error (subject corrects towards target instead of away) had been made. As a result, those anti-point trials with a detectable anti-point error had two latencies: an early error latency when subjects moved 2 cm in the wrong direction (towards the target); and a subsequent latency when the subject had reversed the initial error and had moved 2 cm beyond the initial position in the instructed direction (away from the target).

Results

Central point trials, i.e. those in which the LED did not jump, were not analysed. Of the remaining perturbation trials, 4.2% were discarded overall due to erroneous responses (i.e. failure to reach the appropriate target) or equipment failure. Within the anti-point condition, overall 8.75% of trials were discarded. The surviving anti-point trials were investigated further. Overall, 23% (range across subjects: 7–54%) of anti-point trials showed a detectable anti-point error in both the initial and reproduced path. An anti-point error was defined as having occurred if the subject moved 2 cm in the incorrect direction, and 59.5% of anti-point trials (range: 12–86%) showed no detectable anti-point error in either the initial or the reproduced path. A further 5.8% (range: 0–18%) showed an anti-point error only in the initial path and not in the reproduced path, while 11.7% (range: 0–31%) showed an anti-point error only in the reproduced path and not in the initial path. In these last two cases, motor performance and motor awareness clearly differed qualitatively, and could not be compared directly. As such comparisons were our main interest, these trials were excluded from all further analyses. Thus, the anti-point trials analysed were of two types only: those which contained no anti-point error on either the initial or the reproduced movement, and those which contained anti-point errors in both the initial and the reproduced movement.

In contrast, when subjects made correct adjustments towards the target (on pointing trials) or away from it (on anti-pointing trials), these adjustments were always also present (100%) in the reproduced path.

Uncorrected t-tests on both temporal and spatial measures (see later) found no significant differences between left and right movements (all P>0.6). Therefore, all data were collapsed across side for further analyses.

Correction latencies of initial movements

The latencies of the initial paths were compared to establish the relationship between the point and anti-point movements. Trials in the anti-point condition were divided into those with detectable anti-point errors and those without. In some anti-point trials two latencies could be calculated: the standard latency (i.e. when the subject had moved 2 cm in the correct direction) and the anti-point error latency (i.e. when the subject had moved 2 cm in the incorrect direction). The deviation latencies are shown in Table 1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Point</th>
<th>Anti-point (no error)</th>
<th>Anti-point (with error)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anti-point error</td>
</tr>
<tr>
<td>Latency</td>
<td>354</td>
<td>470</td>
<td>358</td>
</tr>
<tr>
<td>SD</td>
<td>68</td>
<td>152</td>
<td>75</td>
</tr>
</tbody>
</table>
Planned contrasts showed that the anti-point (no error) latency was significantly longer than the point latency and the anti-point error latency ($F_{(1, 22)} = 15.01, P = 0.001$). There was no significant difference between the point latency and the anti-point error latency ($F_{(1, 22)} = 0.003, P = 0.96$).

Spatial disparity between initial and reproduced movements (awareness gap)

The differences between the initial paths and the reproduced paths were then considered in order to compare motor performance with motor awareness. As they were often of different temporal lengths, the data were spatially resampled so that direct comparisons could be made (as described in 'Materials and methods'). The data were spatially resampled at 1-cm intervals in the $Y$ direction and the average $X$ values at the corresponding locations were computed to produce an average spatial path (Fig. 5).

It can be seen in Fig. 5 that the reproduced path in the point condition consistently showed less lateral deviation than the initial movement. This shows an underestimation of both the timing and extent of their correction. The reproduced path in the anti-point condition does not show this awareness gap. Rather, it is remarkably accurate when compared to the initial path. Due to the averaging and resampling of the data, anti-point errors cannot be seen in this figure.

The extent of the estimation errors was calculated by subtracting the $X$ value of the reproduced movement from the $X$ value of the initial movement at 1-cm intervals (see Fig. 3 for further details of how the estimation errors were calculated). This resulted in two types of estimation error: underestimation, when the subject was unaware of both the speed and the extent of their corrected movement; and overestimation, when the subject was hyperaware of the deviation in their movement (shown schematically in Fig. 3). These measures can be treated as positive and negative awareness gaps respectively. These are spatial counterparts of the awareness delay calculated in the latency analysis. By summing the total error, this qualitative distinction is lost. Therefore, in order to investigate it fully, the over- and underestimations were calculated separately for each trial. The sum of each estimation error was considered for each condition (see Fig. 6).

There was significant underestimation in the pointing condition ($t_{(1)} = 4.16, P = 0.002$). There was significant overestimation in the anti-pointing condition ($t_{(1)} = -4.04, P = 0.002$). To retain an overall $P$ value of 0.05 following familywise Bonferroni correction for multiple comparisons, a critical level of $P = 0.025$ was used for these $t$-tests.

Temporal discrepancies between initial and reproduced deviation latencies (awareness delay)

Typical trials for one subject can be seen in Fig. 7. In panels a and b there is no target displacement. A smooth reaching movement can be seen in the $Y$ dimension with minimal lateral displacement. In panels c and d there is a leftward target displacement and a corresponding leftward
motor adjustment in the \( X \) dimension. A prolonged deceleration can also be seen in the \( Y \) dimension. In panels e and f there is a rightward target displacement and an appropriate leftward motor adjustment in the \( X \) dimension. However, this adjustment (e) occurs late in the progress of the reaching movement. In panels g and h there is a rightward target displacement and the subject makes an initial anti-point error followed by a correct leftward adjustment. This produces first a rightward adjustment, and then a leftward adjustment, in the \( X \) dimension.

The initial and reproduced latencies were calculated as described in 'Materials and methods'. The difference between these values was defined as the awareness delay, with a positive value indicating that the correction occurred later in the reproduced trial than in the initial trial (Table 2).

The initial and reproduced deviation latencies were compared (Fig. 8). Previous research indicated that awareness of a correction would be delayed relative to the actual onset of the correction in the standard pointing task (Castiello et al. 1991); therefore a one-tailed \( t \)-test was performed in this condition. No prediction was made for the anti-point conditions; therefore two-tailed tests were performed on these data. The anti-point (with error) was not analysed further as artefacts from the latency analysis could potentially have affected the results. To retain an overall \( P \) value of 0.05 following familywise Bonferroni correction for multiple comparisons, a critical level of \( P=0.0166 \) was used for these \( t \)-tests.

There was a significant difference between the initial and reproduced deviation latencies in the point condition.

**Fig. 7** Typical trials from one subject, showing raw paths of initial and reproduced movement pairs for each condition

**Fig. 8** Deviation latencies (ms) of initial and reproduced paths

**Table 2** Mean deviation latencies (ms) (and standard deviations) of initial and reproduced paths

<table>
<thead>
<tr>
<th>Path</th>
<th>Condition</th>
<th>Anti-point (no error)</th>
<th>Anti-point (with error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial path</td>
<td>Point</td>
<td>354 (68)</td>
<td>761 (226)</td>
</tr>
<tr>
<td></td>
<td>Anti-point (no error)</td>
<td>470 (152)</td>
<td>358 (75)</td>
</tr>
<tr>
<td>Reproduced path</td>
<td>Anti-point (no error)</td>
<td>455 (135)</td>
<td>701 (292)</td>
</tr>
<tr>
<td>Awareness delay</td>
<td>Anti-point (with error)</td>
<td>341 (127)</td>
<td>61 (288)</td>
</tr>
</tbody>
</table>
Discussion

First, this experiment confirms that rapid corrections can be made to an ongoing pointing movement in response to a target shift. The movements reported here resemble those seen in previous reports (Castiello et al. 1991; Day and Lyon 2000; Pélisson et al. 1986). In anti-point blocks, subjects frequently made anti-point errors. These resembled those reported by Day and Lyon (2000), namely, early deviations towards the target at a latency similar to those seen in previous studies (Castiello et al. 1991; Pélisson et al. 1986). However, the latency for anti-point errors was significantly lower than for anti-point trials, which primarily measured stimulus awareness, and this study, which used movement reproduction as an index of motor awareness. Our results on awareness of pointing corrections agreed in some respects with those of Castiello et al. (1991), who found that subjects significantly underestimated their own ability to correct for target perturbations. Likewise, we found significant spatial awareness gaps and temporal awareness delays between movement corrections in the initial and reproduced movement. This similarity is interesting due to fundamental methodological differences between Castiello et al.'s (1991) study, which primarily measured stimulus awareness, and this study, which used movement reproduction as an index of motor awareness.

To investigate this further, the latencies in the point and anti-point conditions were considered. Whereas Castiello et al. (1991) found a delay of some 300 ms between motor correction and perceptual awareness, we found a much smaller delay of only 36 ms between motor correction and motor awareness, as inferred from movement reproduction. Our effect was nevertheless statistically reliable. Delayed awareness of pointing corrections was accompanied by attenuated awareness of their spatial characteristics. Subjects' reproduced trajectories showed significantly lower amplitudes of correction than their initial trajectories.

In anti-point trials, in contrast, this effect was reversed; subjects slightly overestimated the efficiency of their corrections. This finding suggests a qualitative difference in motor awareness between pointing and anti-pointing. Interestingly, anti-point errors did not show the awareness delay characteristic of the rapid point corrections with which they were kinematically similar. One possibility for this anomaly would be the existence of a special mechanism that allows reconstruction of awareness in error situations. Such a mechanism would have obvious ecological benefits as it would allow a full analysis of the erroneous behaviour, allowing both correction and a learning opportunity.

Like Day and Lyon (2000), we agree that there are two classes of correction: rapid automatic corrections and slower intentional corrections. It has also been argued that pointing corrections may differ from other classes of movement in which stimulus and response are less directly connected (Pisella et al. 2000). Pisella et al. (2000) observed fast movement corrections following changes in target location, but much slower corrections following changes in target colour. They also noted that a parietal patient failed to perform fast corrections following changes in target location, and they suggested that automatic corrections depend on a circuit involving the parietal cortex. Since these visuomotor adjustments have also been found to have a subcortical dependence (Day and Brown 2001), we suggest that a parieto-ponto-cerebellar loop mediates automatic corrections. Such a loop has also been implicated in a recent PET study (Desmurget et al. 2001) that considered reaching to a moving target. Desmurget et al. (2001) specifically identified activity in parietal and cerebellar regions, as well as primary motor cortex. Our results suggest that this circuit has attenuated access to conscious awareness. In contrast, when stimulus and motor response are arbitrarily or even counterintuitively related, a much slower intentional action system is used (Frith and Done 1986). This circuit is characterised by the involvement of conscious awareness. Previous studies of awareness have focused on perceptual phenomenology (Castiello et al. 1991; Pélisson et al. 1986; Rees 2001), but we have shown that the intentional action route also elicits a distinctive motor awareness.

Previous studies have explicitly addressed the relationship between motor performance and awareness (Castiello et al. 1991; Pélisson et al. 1986). However, these focused on dissociations between motor performance and perceptual awareness of target shifts: such a dissociation is not surprising given the separation between perceptual and motor systems in the brain. We believe ours is the first study to investigate directly the relationship between motor performance and motor awareness of corrections in the double-step task. Interestingly, we found that motor awareness can dissociate from motor performance. Even more importantly, the way it does so appears to depend on the nature of the action. Thus, we found that motor awareness of an online correction is delayed in an automatic correction to an overt target shift.
However, this awareness gap is reversed in anti-pointing tasks.

One simple explanation for these findings would be that the two conditions, pointing and anti-pointing, utilise two routes, for example the 'direct' and 'slow' routes of Frith and Done (1986). A two-route model could explain both the delayed latencies in intentional (anti-point) movements when compared with an automated, stimulus driven (point) movements, and the differential awareness between the two. That is, the slower, intentionally modulated route could lead to subjects not only being aware of their intentional corrections but being more aware of the intention than of the action itself. An automated movement, however, could largely bypass this intentional system and instead emphasize goal attainment, with only basic and delayed awareness of the movement itself.

However, this explanation would not account for subjects' awareness of erroneous early corrections in the anti-point condition. From the point of view of motor performance, anti-point errors were motorically identical to the early corrections seen in pointing trials. Yet they showed an anticipatory awareness in contrast to the delayed awareness seen in pointing tasks. It seems unlikely that anti-point errors arise from the same motor system as the anti-point movement itself, either psychologically (as they were contrary to the task) or physiologically (as they had much shorter latencies). In this situation, the performance of anti-point errors resembles that of standard pointing corrections. However, the awareness of anti-point errors is characterised by an anticipatory awareness relative to actual motor performance, comparable to that observed for awareness of the main anti-point correction. Thus, anti-point errors resemble normal pointing corrections in their performance aspects, but resemble anti-point corrections in their awareness aspects.

This provides another example of dissociation between motor performance and motor awareness. In the specific case of anti-point errors, then, our results seem incompatible with the view that fast visuomotor corrections never enter conscious awareness (Castiello et al. 1991; Pélésson et al. 1986). Instead, the critical feature appears to be whether the visuomotor correction matches the intended movement. If the correction does match the intended movement, awareness of the correction is minimal. But if the correction is an unintended motor error, it enters awareness fully, and without delay. Our results thus suggest that the same motoric output elicits very different awareness depending on whether or not a controlling intentional supervisory system has been brought into play.

To summarise, when the automatic motor system guides the hand towards a target the precise details of the movement correction do not enter awareness, producing an awareness gap. However, in anti-pointing, the intention is to perform a quite different action to that suggested by the target shift. In that case, the automated system responsible for visuomotor corrections can result in a consequence that is inappropriate (e.g. following the target in an anti-pointing task). In this case, the movement becomes subject to scrutiny by a supervisory system that suppresses the automated correction allowing the slower, controlled, anti-point. Movements controlled by this system become conscious and the subject is able to accurately report their deviation. However, this controlling mechanism is quite slow, and may fail to suppress the fast visuomotor correction generated by the movement of the motor system. In this situation, an anti-point error occurs. The early correction must then be halted and the direction of the movement reversed by the slower supervisory system. Our data suggest that awareness of the movement may begin from the time the supervisory system is invoked, rather than from the (later) time when it begins to correct the movement. Consequently, early visuomotor corrections in anti-pointing can enter conscious awareness, even though motorically similar corrections in standard pointing elicit only attenuated awareness. Since the key difference between anti-pointing and standard pointing lies in the subject's intention, this result suggests a strong role of intention in motor awareness.

In conclusion, we have found that subjects are able to report motor awareness through movement repetition. It was found that motor awareness can be dissociated from motor performance. Contrary to previous findings, subjects can be aware of fast visuomotor corrections. However, this awareness is dependent upon the relationship between the movement and the intention of the subject. We suggest that involvement of a supervisory system is always accompanied by awareness of action (Jack and Shallice 2001).

References


Appendix B


Incorporating data from Experiment 4
Consistent chronostasis effects across saccade categories imply a subcortical efferent trigger

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Abstract

Saccadic chronostasis refers to the subjective temporal lengthening of the first visual stimulus perceived after an eye movement, and is most commonly experienced as the “stopped clock” illusion. Other temporal illusions arising in the context of movement (e.g. “intentional binding”) appear to depend upon the volitional nature of the preceding motor act. Here we assess chronostasis across different saccade types, ranging from highly volitional (self-timed saccades, antisaccades) to highly reflexive (peripherally-cued saccades, express saccades). Chronostasis was similar in magnitude across all these conditions, despite wide variations in their neural bases. The illusion must therefore be triggered by a “lowest common denominator” signal common to all the conditions tested and their respective neural circuits. Specifically, it is suggested that chronostasis is triggered by a low-level signal arising in response to efferent signals generated in the superior colliculus.

Introduction

When subjects glance at a silently ticking clock, they often initially think that the clock has stopped; then, after a short pause, the second hand begins to move again. Recently, an experimental paradigm has been introduced permitting the quantification of this subjective lengthening of the post-saccadic stimulus, and the effect has been termed “chronostasis” (Yarrow, Haggard, Heal, Brown, & Rothwell, 2001). Observers fixated a cross on one side of a monitor then made a saccade to a target “0” on the other side. Eye movement triggered a change of digit to a “1” which remained on screen for 400-1600 ms. Subsequent digits (“2”, “3”) remained on the screen for 1 s each, culminating in the appearance of a “4”. Subjects indicated whether the time they saw the “1” was longer or shorter than that for the subsequent digits, allowing matched estimates to be derived. In general, subjects overestimated the time they had seen the saccadic target by about 120 ms.

Saccadic chronostasis depends upon eye movement. It is found following a saccade, but not during static viewing or when the counter is moved towards fixation while the eye remains still. The effect also depends upon the size of the preceding eye movement, with illusion size increasing approximately linearly with the duration of a
saccade. The illusion can be disrupted by some but not all changes in the visual scene occurring mid saccade. Specifically, when the counter is noticeably displaced the illusion disappears (Yarrow et al., 2001). These data suggest the following explanation of the effect. During a saccade, retinal blur and mechanisms of active suppression degrade visual input (Ross, Morrone, Goldberg, & Burr, 2001) leaving a "gap" in perception, yet we have continuous awareness of the state of objects in the world. The brain simply assumes that the information in the post-saccadic image has remained constant throughout the saccade, providing the continuity we experience. Hence, post-saccadic events are antedated to just before saccadic onset. This antedating is a specific construction of the brain: when sensory evidence suggests that this assumption is incorrect (as when the target is perceived to have jumped) antedating does not occur and chronostasis is not observed.

Saccadic chronostasis findings have recently been supplemented by reports of similar illusions arising after reaching movements (Yarrow & Rothwell, 2003) or in the context of shifts of auditory attention (Hodinott-Hill, Thilo, Cowey, & Walsh, 2002). Two theories have been proposed to explain chronostasis across these various experimental situations. Hodinott-Hill et al suggested that the critical factor may be arousal, which is known to influence time estimation (Treisman, Faulkner, Naish, & Brogan, 1990; Wearden, Edwards, Fakhri, & Percival, 1998). Arousal might increase the speed of a hypothetical pacemaker-accumulator internal clock (Treisman, 1963) and lead to overestimation of time immediately after a movement. By contrast, Yarrow and Rothwell have argued that the illusion arises when movement produces uncertainty about the onset of a sensory event. They suggested that in saccadic chronostasis the initial response of neurones with receptive fields that shift in the temporal vicinity of a movement (Duhamel, Colby, & Goldberg, 1992; Walker, Fitzgibbon, & Goldberg, 1995; Umeno & Goldberg, 1997) may be used as a time marker for the onset of perceptual properties that are only established later (Yarrow et al., 2003). The idea that a specific neural event might subsequently be used as a time marker for temporal judgements has a clear precedent. It was used by Libet, Wright, Feinstein, and Pearl (1979) to explain why trains of direct electrical stimulation of a duration just long enough to elicit tactile sensation (approx. 200 ms) appear delayed relative to stimulation of the skin if applied to somatosensory cortex, but not when applied to the medial lemniscus (see Pockett, 2002, for a critique).
The arousal account cannot give a satisfactory explanation for a number of experimental results, such as the illusion's dependency on saccade size and the spatial continuity of the saccade target. However, the alternative receptive-field-shift account also faces difficulties. The pronounced variability across cells in the timing of receptive field shifts makes this event unsuitable as a time marker (Kusunoki & Goldberg, 2003). In reformulating this account in the discussion, we will suggest that receptive field shifts (and other processes relating more directly to duration estimation) are triggered by a specific efference copy signal that may be generated elsewhere in the brain. Receptive field shifts may then underlie conscious visual perception at the time chronostasis occurs; subjective experience might effectively reflect an average of the temporally smeared representation provided by a large number of neurones.

The present experiments do not address the arousal and receptive field shift hypotheses directly, but were instead designed to assess the neural/cognitive level at which the signal that triggers the saccadic chronostasis illusion arises. In the original saccadic experiments, chronostasis was elicited using a self-timed saccade. However, a number of different kinds of saccade have been identified (e.g. Deubel, 1996) differing primarily along a dimension which might be termed the intentional-reactive axis. To assess whether chronostasis arises at the level of 1) volitional or 2) low-level oculomotor processes, we therefore compared the illusion's magnitude for various types of saccade. This comparison can offer data to refine both the arousal and receptive field shift accounts, but will not necessarily support one account over the other. We provide a more direct test of these alternative hypotheses elsewhere (Yarrow, Haggard and Rothwell, submitted).

*Experiment 1: Pro/anti saccades.* Chronostasis is not the only temporal illusion that has recently been reported in the context of movement. Haggard, Clark, and Kalogeras (2002) made use of the Libet clock paradigm to investigate the relationship between the perceived time of various combinations of movements and briefly presented auditory stimuli. Presenting a tone after a movement caused the perceived times of occurrence for both events to be drawn closer together, as if they had been temporally bound. This finding shows a striking resemblance to chronostasis, where a post-movement event is antedated to the point of movement initiation. A second result was that this binding effect disappeared (and was even reversed) in the absence of volition, when transcranial
magnetic stimulation (TMS) was applied over the contralateral motor cortex to elicit a movement. This led the authors to term their effect “intentional binding,” considering it to depend upon the volitional nature of the motor act.

In light of these experiments, it seems natural to ask whether chronostasis also depends upon volition. Varying the self-timed/cued nature of a saccade approximates the manipulation of volition provided by comparing self-timed actions with movements induced by TMS. If chronostasis has a volitional origin, we might reasonably predict that chronostasis will be reduced for cued saccades relative to volitional saccades. In Experiment 1 chronostasis was therefore measured following cued saccades made in response to a sudden and unpredictable peripheral onset (pro saccades). In addition, anti-saccades (saccades made in a direction opposite to a sudden peripheral onset) were considered. This task requires active suppression of a dominant response, yielding a high volitional component and slow reaction times (Hallett, 1978). In anti saccades, the intention to move should occur at a normal latency after the instructive stimulus. However, this intention is translated into an actual eye movement only after a much longer delay than in pro saccades because of the substantial additional time taken to inhibit the prepotent, reflexive response to saccade towards the target instead of away from it. It follows that the temporal interval between the time of intention and the time of movement onset will be greater in the anti-saccade condition than in the pro-saccade condition; the anti-saccade condition increases the separation between these events. A comparison between pro and anti saccades allows us to investigate whether the chronostasis effect is tied to the intention or to the movement. Specifically, if we assume that the signal driving chronostasis were to arise early in motor preparation (i.e. before the processes that produce a reaction time deficit for anti-saccades, such as the re-specification of saccade direction) greater chronostasis is anticipated in the anti-saccade than the pro-saccade condition. Effect size should be enhanced in this condition by an amount roughly commensurate with the observed increase in reaction time.

Experiment 2: Express saccades. Whichever account of chronostasis is favoured, information about the eye movement itself must be transmitted to the neural structures responsible for temporal perception in order to obtain the observed modulation of subjective time. We therefore consider where in the motor system such a signal arises. The oculo-motor plant receives its primary input from the brainstem burst generators of
the reticular formation (Moschovakis, Scudder, & Highstein, 1996). Different types of saccade selectively recruit additional higher cortical areas during saccade generation (Scudder, Kaneko, & Fuchs, 2002). For example, typical peripherally-cued saccades, arising with a latency of around 180 ms, may have a different neural basis from express saccades, made with a latency of 130 ms or less and elicited using a gap paradigm (Fischer & Ramsperger, 1984). So far, chronostasis has only been demonstrated for self-timed saccades. If an effect of similar magnitude arises for other saccades, then the information used to adjust perceptual experience must arise in areas common to both types of saccade. Hence while all saccades involve low-level dedicated areas such as the superior colliculus and the brainstem (Hopp & Fuchs, 2002) certain kinds of saccade additionally recruit areas in frontal and parietal cortex. If these cortical structures contribute signals necessary for chronostasis effects, then no illusion would be predicted following saccades that do not engage such regions. Therefore, in experiment 2, a comparison was made between express saccades, peripherally-cued saccades and self-timed saccades to assess the degree of cortical involvement in saccade generation required to produce chronostasis.

Results

Experiment 1. In separate blocks, subjects made speeded pro or anti saccades out from central fixation in response to a peripheral open box cue (Fig 1). Following correctly targeted saccades, they judged the duration of a variable (400-1600 ms) circular stimulus, appearing during the saccade and therefore only perceived at refixation, relative to a reference (1000 ms) stimulus presented just afterwards at the same location (forced choice longer/shorter). These judgements were used to derive a subjective duration estimate in each condition. This is defined as the time for which the variable-duration stimulus needed to be present to be judged as of equal duration to the reference stimulus. In a constant fixation control condition, subjects fixated a peripheral cross which disappeared briefly prior to presentation of the same sequence of a variable-duration stimulus followed by a reference stimulus.

Eye movement measures were similar across conditions. Saccades took an average of 58.4 ms in the pro-saccade condition and 61.2 ms in the anti-saccade condition. Mean reaction times, however, differed, being 274 ms in the pro-saccade
condition and 335 ms for anti-saccades, a predicted and highly significant difference of 61 ms ($t = 6.52$, $df = 25$, $p < 0.001$).

Figure 3(a) shows mean corrected time estimates in all three conditions. The estimated duration of 1063 ms in the constant fixation control condition was just above, but did not differ significantly from, the target value of 1000 ms. Estimates were substantially reduced in both the pro- and anti-saccade conditions, by an identical 90 ms relative to control. ANOVA showed a significant difference across conditions ($f = 5.448$, $df = 2$, 50, $p = 0.007$) with pairwise follow ups showing significant differences between control and pro-saccade ($p = 0.007$) and control and anti-saccade ($p = 0.015$) conditions.

Experiment 2. Because express saccades are typically elicited in the absence of a structured visual background (e.g. Hopp et al., 2002) Experiment 2 took place in darkness using red/green light emitting diodes (LEDs) as stimuli. A red target stimulus switched to become green mid-saccade to provide the intervals used in duration judgements. Variance in time judgements increases with the duration of the interval that is being judged (Allan, 1998). Therefore the duration of the reference stimulus was reduced from 1000 ms (Exp. 1) to 500 ms, with the variable stimulus taking a value between 100 and 900 ms. Subjects completed three saccade conditions (self-timed saccades, peripherally-cued saccades and express saccades; see Fig 2) and a constant fixation control. Self-timed saccades lasted, on average, 77 ms. Cued saccades were made with an average latency of 197 ms, and lasted for an average of 72 ms. Saccades elicited in a gap paradigm (Saslow, 1967) yielded an average latency of 150 ms. Only those trials in which saccadic RT was between 70 and 130 ms (mean 37% of acceptable trials) were classified as express saccades and used to derive subjective duration estimates in the express condition. Saccades in such trials lasted an average of 79 ms.

Mean subjective duration estimates are shown in Figure 3(b). Once again, the control estimate was a little above the veridical value of 500 ms but this difference was not significant. As in the pro/anti saccade experiment, estimates were substantially reduced in the various saccade conditions, with effect sizes of between 135 and 192 ms relative to control. ANOVA showed a significant difference across conditions ($f = 24.306$, corrected $df = 3$, 30, $p < 0.001$) with pairwise follow ups showing significant
differences between the control and each of the saccadic conditions (all p < 0.001) while the saccadic conditions did not differ significantly from one another.

Discussion

The two experiments reported here suggest that the size of the chronostasis effect is approximately similar in all types of saccadic eye movements tested (self timed, cued, anti, pro, express) despite wide variations in underlying neural mechanisms. We will argue below that this is compatible with an efference copy signal arising late in saccade generation, perhaps in the superior colliculus, that influences other areas responsible for visual awareness and timing operations. Firstly, however, we will deal with two subsidiary features of the data: a trend towards biased estimates in the constant fixation control conditions, and the different effect magnitudes found in Experiments 1 and 2.

In our experiments, subjective duration estimates were established in both constant fixation and saccade conditions. The inclusion of a constant fixation condition controlled for any individual differences and systematic biases in temporal judgements. Even under optimal conditions, duration estimates derived from comparison tasks like that used here are often biased. This bias, known as the time order error, is notoriously difficult to predict (Allan & Gibbon, 1994; Hellstroem, 1985). It may explain the non-significant trend evident in both experiments for subjective duration estimates to exceed the veridical reference stimulus duration under constant fixation conditions. The time order error should be identical in our constant fixation and saccade conditions. We therefore estimated the magnitude of the chronostasis illusion as the difference between these conditions.

Although chronostasis was clearly present for all types of saccade tested here, there was a trend towards larger effect sizes in the second experiment. While a number of procedural changes between the two experiments may have been responsible, differences as large as these are often seen for different groups of subjects in separate chronostasis experiments, even when the procedure is essentially unchanged (cf. Yarrow et al., 2001). For this reason, our statistical inferences were based only on differences between conditions within a single group of subjects. Chronostasis is constant across different reference stimulus durations (Yarrow et al., submitted) and
when the timing of the mid-saccadic stimulus change is altered (Yarrow et al., 2001) so these changes are unlikely to have influenced our results across experiments. The illusion has been shown to increase approximately linearly with the duration of a saccade (Yarrow et al., 2001) and saccades were slightly slower in Experiment 2, but the size of this difference (around 15 ms) suggests that it can only offer a partial explanation of the increase in illusion size. It is possible that the subtlety of the mid-saccadic stimulus change in Experiment 2 (a change from red to green for a stimulus initially perceived only in the periphery) may have enhanced the illusion, given that noticeable changes in the position of the target stimulus at this time are known to substantially reduce chronostasis (Yarrow et al., 2001). Changes in form, like those used in Experiment 1, may have been registered as a greater disruption to the continuity of the visual scene.

The main results of the two experiments are, however, very clear. In the first experiment the hypothesis that chronostasis would increase in the anti-saccade condition was not supported. Reaction times between these two conditions differed by 61 ms; if chronostasis involved antedating the post-saccadic percept to a pre-motor event occurring prior to the (re)specification of saccade parameters required in the anti-saccade condition, an increase in effect size of similar magnitude would be expected. This did not emerge. These data therefore suggest that volition is not a critical factor in producing chronostasis. The results of the second experiment reinforce this conclusion. The illusion appears to be a relatively low-level phenomenon since it even arises for highly reflexive eye movements. Thus the time-marking signal employed to trigger chronostasis probably arises from some basic motor process downstream of any volitional intervention.

Turning to the issue of anatomical localisation, the express saccade condition provides the most revealing result. Because this kind of saccade is the most basic studied thus far (Hopp et al., 2002) it effectively limits the regions from which a relevant movement-related command might arise. More complex types of saccades make use of higher cortical areas, but all saccades ultimately rely on areas projecting directly to the brainstem burst generator (Scudder et al., 2002). Since chronostasis appears ubiquitous and of comparable magnitude for all saccades, those cortical areas involved in more "cognitive" saccades, but which are not typically involved in low-level saccade generation, cannot be the source of the signal that triggers the illusion.
Single pulse transcranial magnetic stimulation of the posterior parietal cortex, for example, has been shown to affect the onset time and metrics of memory guided saccades (Muri et al., 2000). This area is almost certainly not involved in express saccades however (Hopp et al., 2002). Since chronostasis was found for express saccades, posterior parietal cortex is unlikely to give rise to signals important in triggering the effect, though it may contribute to generating the subjective content of the illusion.

Expanding on this point, the chronostasis effect recalls pre-saccadic receptive field shifts originally demonstrated for neurones in the lateral intraparietal area (Duhamel et al., 1992). However, such remapping is evident in other regions including the superior colliculus, frontal eye fields and early visual cortical areas (Walker et al., 1995; Umeno et al., 1997; Nakamura & Colby, 2002) so a remapping explanation of chronostasis remains viable. More importantly, remapping in regions like the lateral intraparietal area is presumably triggered by efference-copy signals arising from other saccade-related areas (Sommer & Wurtz, 2002). When excluding cortical areas based on their failure to play a role in the generation of express saccades, we consider only the source of any signal initiating the processes that underlie saccadic chronostasis. The location from which this signal arises need not be the same as the location(s) which construct the experiences of subjective time and visual awareness.

Aside from parietal cortex, a number of other cortical sites are undermined by our results from express saccades. The prefrontal cortex can be excluded by similar arguments to those used for parietal areas. Transcranial magnetic stimulation over prefrontal cortex increases the likelihood of express saccades, suggesting that it typically inhibits these responses and does not play a role when they occur spontaneously (Muri et al., 1999). The frontal eye fields are better candidates. They project to the superior colliculus and have weak but direct projections to the brainstem burst generator (although the extent and functional significance of these links is debatable; see Scudder et al., 2002, for an overview). They also show retinotopic mapping like that in the superior colliculus and consistent with an important role in determining the spatial metrics of saccades (Thompson & Bichot, 1999) and have recently been shown to facilitate responses in early visual areas in a manner consistent with premotor views of attention (Moore & Armstrong, 2003). These areas are candidate loci for a signal giving rise to chronostasis. However, some authors have
suggested that they are relevant for voluntary but not reflexive saccades (Schneider & Deubel, 2002). Crucially, their causal role in the generation of express saccades is questionable (Hopp et al., 2002). Schiller and colleagues (Schiller, Sandell, & Maunsell, 1987) showed that lesions of the frontal eye fields had no long-term effects on the production of express saccades, in contrast to lesions of the superior colliculus. It has recently been suggested that neurons in the frontal eye fields discharge in a manner consistent with a role in express saccade generation (Everling & Munoz, 2000). However, this conclusion remains contentious (Hopp et al., 2002); the observed patterns of cell discharges may reflect efference copy information arriving from the superior colliculus rather than motor commands. There is therefore good reason to doubt that the signal triggering chronostasis arises in the frontal eye fields.

A number of other anatomical regions are uncontroversially involved in all the saccade types employed here. In particular, afferent information from the oculomotor plant remains a viable source. The delayed nature of sensory feedback places this interpretation at odds with the remapping account of chronostasis, which suggests that the system responsible for timing the post-saccadic stimulus is effectively being switched on early during saccade generation. However, feedback from ocular muscles and related sources might reasonably result in the transient increases in arousal suggested by Hodinott-Hill et al. (2002). Such feedback could also play a role if temporal experience is modified "after the event", perhaps reflecting the ongoing revision of conscious awareness in response to updated information (Dennett & Kinsbourne, 1992). Future experiments could investigate the role of afferent information by assessing chronostasis following externally induced perturbations of eye position.

Returning to an outflow explanation, the brainstem burst generator is clearly a good candidate for the signal triggering chronostasis, since it is the final source of efferent information for saccade generation. This region is presumably active in all saccades. However, we suggest a region active slightly earlier than the brainstem burst generator in movement generation: the superior colliculus. This suggestion is based on this region's known anatomical connections, and in particular on recent data demonstrating the transmission of efference-copy information upstream from the superior colliculus to cortical areas (Sommer et al., 2002). The superior colliculus is widely regarded to be the primary interface with the burst generator (e.g. Scudder et al.,
Lesions here impair saccades, but do not completely prevent saccades occurring via other routes (Sparks, 1986). Electrical stimulation in the superior colliculus can produce saccades with a delay of only 20-30 ms (Moschovakis et al., 1996) but movement-related activation is often seen in collicular cells well in advance of saccade initiation (e.g. Walker et al., 1995). Although the deep layers of the superior colliculus are most widely known for their descending projections involved in the direct control of movement, they also have ascending axons that terminate in the dorsal thalamus and in turn project to the frontal eye fields and the inferior parietal lobule (Sparks, 1986). This pathway has recently been shown to send corollary discharge signals upstream to the frontal eye fields. Monkeys performing a double saccade task failed to fully correct for the displacement caused by the first saccade when this pathway was blocked (Sommer et al., 2002). These authors suggested that signals transmitted via this pathway might trigger receptive field shifts in frontal and parietal regions. Might such a pathway also convey information responsible for chronostasis to areas involved in timekeeping and conscious perception? We speculate that a corollary discharge signal from the superior colliculus could trigger remapping processes in the frontal eye fields or lateral intraparietal area that underlie the extended conscious visual percept experienced in chronostasis experiments. The same collicular signal, or subsequent signals from affected cortical regions, might trigger timing processes, probably involving a network of brain areas including the basal ganglia, lateral cerebellum, supplementary motor area, dorsolateral prefrontal cortex, anterior cingulate cortex and right parietal cortex (Hazeltine, Helmuth, & Ivry, 1997; Macar et al., 2002; Matell & Meck, 2000; Meck, 1996; Meck & Benson, 2002; Rao, Mayer, & Harrington, 2001).

It should be noted that the logic applied here assumes a single neural locus as the origin of the chronostasis trigger signal. Of course this information could be transmitted from different sites and via multiple routes, depending on the nature of the movement. For example, receptive field shifts are known to occur in several brain areas (Duhamel et al., 1992; Walker et al., 1995; Umeno et al., 1997; Nakamura et al., 2002) perhaps with different temporal dynamics. An interaction between various signal sources (and regions receiving and acting upon such signals) might help to explain the trend observed in the express saccade experiment for a greater effect in the cued condition relative to express and self-timed saccades, should future research show it to be reliable.
Saccadic chronostasis appears to be a prime example of a motor act interacting with sensory systems to alter perceptual experience, reflecting the indivisibility of the two systems (Hommel, Musseler, Aschersleben, & Prinz, 2001). The present data show that the signal used to achieve this modification of perception can arise rather late in the chain linking decisions to motor actions, perhaps at the level of the final oculomotor command itself. These experiments point to the generality of the phenomenon of saccadic chronostasis. The process appears to be operating regardless of the duration of the post-saccadic stimulus or the kind of saccade that is being made, suggesting that the illusion is ubiquitous in our everyday experience and may well be filling in the experiential gaps left by saccadic suppression. A detailed neural model of exactly how chronostasis arises will be the topic of future research.

**Methods**

**Statistics**

Standard parametric tests were used (repeated-measures ANOVAs, t-tests, logistic regression) with $\alpha = 0.05$ and Bonferroni corrections applied for multiple comparisons. For repeated measures ANOVAs, sphericity violations were controlled using the Greenhouse-Geisser correction when $\varepsilon$ was below 0.7 and the Huynh-Feldt correction when Greenhouse-Geisser $\varepsilon$ was above 0.7 (Howell, 1997).

**Pro/anti saccade experiment**

26 subjects (15 male, mean age 30.5, SD 7.8) participated. They sat before a 22” CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 41 cm using an adjustable chin rest. Horizontal eye movements were recorded from the left eye using an infra-red eye tracker (Microguide 1000 spectacles, low-pass filtered at 40 Hz) and sampled at 200 Hz. Stimuli were black or red on a white background, subtending 1.1° (crosses and open circles) or 3.3° (open squares). The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

A repeated-measures design was employed with three conditions: pro-saccade, anti-saccade and control (see below). Trials from each condition were presented in
separate blocks, with six blocks per condition. A single block was completed from each condition in turn, with order counterbalanced across subjects (first 24 subjects) or completed in a random order (final two subjects, both investigators, who completed the 18 blocks and a further 12 blocks from two extra conditions not reported here).

For saccade blocks of both kinds, black crosses were initially displayed 20° to the left and right of a central red cross. In pro-saccade blocks, subjects fixated the red cross and initiated the trial with a mouse key press. 500 ms later a black outline box appeared around one or other peripheral cross, directing the subject to make a speeded saccade in that direction. The box appeared randomly to the left or right on each trial. In anti-saccade blocks, the same sequence of stimuli was used, but subjects were required to saccade to the cross around which the box had failed to appear (i.e. in a direction opposite to it). Eye movement triggered the black cross to be replaced with a circle when the saccade had travelled one fifth of the distance to target. The circle remained on screen for 400-1600 ms. It then disappeared, to be replaced by a red circle (the comparison stimulus) after 500 ms. Subjects indicated whether the time they saw the first circle was longer or shorter than that for which the comparison circle was displayed (exactly 1000 ms). The duration of the first circle was controlled by a modified binary search (MOBS) procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 600-1400 ms, five reversals to terminate) that used subjects' previous responses to home in on a value judged equivalent to the duration of the comparison stimulus (Tyrrell & Owens, 1988). Blocks finished when the MOBS had terminated.

Saccade start/end points were calculated automatically using a velocity criterion. Trials where the first saccade recorded did not exceed 90% of the total distance recorded (summed across all detected saccades) were excluded on line and repeated immediately. This led to the rejection of trials in which subjects initially moved their eyes in the wrong direction. In control (constant fixation) trials, subjects initially fixated a peripheral cross at equivalent eccentricity (±20°). It was blanked 400ms after the subject's mouse key press, then replaced after a further 100 ms by the to-be-judged circle, with subsequent stimulus presentation and subject responses as per saccade trials. Position of the fixation cross alternated every trial.

Blocks were of variable length, typically 6-20 trials (excluding those rejected). Subjective duration estimates were obtained by taking the average of the six MOBS
termination values in each condition. In the saccade conditions, each estimate was corrected post hoc to match the time the first circle was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change to a circle. The experiment took around one hour to complete.

Express saccade experiment

Data from 12 subjects (8 male, mean age 32.3, SD 7.0) was used, a further 7 subjects having been initially assessed and found to produce too low a proportion of acceptable express saccades (<10%). Testing was carried out in total darkness. Subjects sat before an adjustable metal frame upon which three two-colour (red/green) LEDs were mounted in horizontal alignment. The LEDs were 22 cm apart, and eye to screen distance was maintained at 60 cm. Saccades from the central to peripheral LEDs were therefore 20° in extent. Other materials were unchanged from Experiment 1.

A repeated-measures design was employed with four conditions: self-timed, cued, express ("gap" paradigm) and control. Trials from each condition were presented in separate blocks, with three blocks per condition. Two subjects completed additional blocks to ensure that logistic regression provided a significant fit in all conditions (see below). Testing was conducted in two sessions (approx. 50 mins each) to prevent fatigue; block order was selected randomly for each subject, with the constraint that at least one block from each condition was presented in each testing session.

For the express saccade blocks, a central red LED provided an initial fixation point. The experimenter sat in an adjacent testing area and viewed a display showing eye position and details of the current trial and block. They initiated the trial with a mouse key press. 300 ms later the LED was extinguished, and after a further 200 ms one of the two peripheral LEDs (randomly selected) was switched on, initially in red, directing the subject to make a speeded saccade in that direction. For cued blocks, the 200 ms blank period was removed. In self-timed blocks, two LEDs were initially switched on (the central one and one randomly selected peripheral one, both red). The experimenter initiated the trial then verbally indicated that the subject could make a saccade whenever they were ready. In all cases, eye movement triggered the red peripheral LED to change colour to green when the saccade had travelled one half of the distance to target. The green LED remained on for 100-900 ms. It then disappeared,
appearing again after a break of 500 ms and remaining on for 500 ms (comparison stimulus).

Because many trials were rejected, and this decision could only be made after the trial had been completed (see below), MOBS were not used to control the duration of the first green stimulus and provide subjective duration estimates. Instead, the duration of the first green LED was selected randomly on each trial from a distribution containing values between 100 and 900 ms in 25 ms increments. The distribution was initially uniform, in the region 300-700 ms, but was updated after each accepted trial according to the generalized P'olya urn (GPU) model proposed by Rosenberger and Grill (1997) with initial urn composition type IV and k = 8. This procedure adjusts the distribution from which values are selected based on previous responses. Hence selection is efficient, producing on average more values close to the subject's subjective duration estimate, but each trial is selected at random, preventing sequential dependency biases that might compromise estimates subsequently produced by logistic regression.

The automatic analysis of saccades was as per the pro/anti saccade experiment, except that the first saccade only had to exceed 80% of the total distance recorded to be acceptable, and the experimenter had on-line access to derived saccade stats and could make corrections. In addition, express saccade trials were only accepted when saccadic RT was between 70 and 130 ms (measured from go stimulus to saccade onset) and cued saccade trials were only accepted when RT was above 130 ms. In control (constant fixation) trials, subjects initially fixated a peripheral red LED (random left/right presentation). It changed to become green 500 ms after the experimenter began the trial, with subsequent stimulus presentation and subject responses as per saccade trials.

Blocks ended after 20 accepted trials. Subjective second estimates were obtained using logistic regression. In the saccade conditions, each trial presentation value was corrected post hoc to match the time the first green LED was displayed following target foveation by subtracting the time the eye was in motion following the triggered change.
References


Yarrow, K., Haggard, P., & Rothwell, J. C. E. Action, arousal, and subjective time. *Submitted for publication*.

Figure legends

Figure 1. Schematic of procedure for pro/anti-saccade experiment. (a) Sequence of visual stimuli. (b) Eye position. A trial from an anti-saccade block is shown (saccade made away from the box-shaped "go" cue). Eye movement triggered the appearance of a circle (frame 3) and subjects were required to compare its duration with that of a reference stimulus (frame 5). In pro-saccade trials, the circle replaced the cross within the box-shaped cue. Stimuli shown in grey were actually displayed in red.

Figure 2. Schematic of procedure for express saccade experiment. (a) Sequence of visual stimuli. (b) Eye position. A trial from a gap (express saccade) block is shown. Red stimuli are shown in grey, green stimuli in black. Eye movement towards the appearance of a peripheral red LED caused it to change colour to green. Subjects were required to compare the duration of this fixated green stimulus (frame 4) to that of a reference stimulus (frame 6). In cued saccade blocks, no gap was inserted between central fixation and peripheral onset (i.e. frame 1 lasted 500 ms and frame 2 was removed). In self-timed saccade blocks, both central and peripheral LEDs were initially displayed, and subjects made a saccade in their own time eliciting the sequence shown in frames 4 to 6.

Figure 3. Mean subjective duration estimates following different kinds of saccade for (a) pro/anti saccade and (b) express saccade experiments. The control conditions show values derived from constant fixation trials. Error bars show standard deviations.
### Figure 1 (Yarrow et al)

<table>
<thead>
<tr>
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<tr>
<td>1</td>
<td>0.5 s</td>
<td>+ + +</td>
</tr>
<tr>
<td>2</td>
<td>Variable (RT)</td>
<td>+ + +</td>
</tr>
<tr>
<td>3</td>
<td>Variable (0.4-1.6 s)</td>
<td>o + +</td>
</tr>
<tr>
<td>4</td>
<td>0.5 s</td>
<td>+ +</td>
</tr>
<tr>
<td>5</td>
<td>1 s</td>
<td>o + +</td>
</tr>
</tbody>
</table>

Eye signal  
Display frame (see above)

### Figure 2 (Yarrow et al)

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<td>○</td>
</tr>
<tr>
<td>2</td>
<td>0.2 s</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Variable (RT)</td>
<td>○</td>
</tr>
<tr>
<td>4</td>
<td>Variable (0.1-0.9 s)</td>
<td>●</td>
</tr>
<tr>
<td>5</td>
<td>0.5 s</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.5 s</td>
<td>●</td>
</tr>
</tbody>
</table>

Eye signal  
Display frame (see above)
Figure 3 (Yarrow et al)

![Graphs showing subject duration estimates](image)

- **Graph a**: Subjective duration estimates with bars for Control, Pro, and Anti conditions.
- **Graph b**: Similar to Graph a, with additional conditions: Voluntary, Cued, and Express.

Values shown in the graphs are 1063, 973, 387, 338, and 395.
Appendix C


The data from this paper is not presented here. It was previously presented towards a MSc at UCL. However, it provides the basis and experimental rationale for Experiments 5, 6 and 7.
The effect of attentional cueing on conscious awareness of stimulus and response

Helen Johnson • Patrick Haggard

Abstract Attending to a cued location in space leads to faster reaction times when a stimulus is presented there. The reasons for this attentional effect, and its specific locus in the information-processing chain between stimulus and response, remain unclear. One suggestion is that attention speeds the conscious detection of stimuli. Surprisingly, this possibility appears not to have been tested directly. To resolve this question, we asked subjects to make simple responses to lateralised targets that followed either a valid, invalid or neutral cue, and to judge the perceived time of the target onset, or of their response, by delayed report of the position of a clock hand. Our results showed that only a small and non-significant part of the attentional effect is due to delayed conscious awareness of the stimulus. The greater part of the attentional effect is localised either subsequent to conscious detection of stimuli or occurs in a separate, parallel processing stream from that which generates the motor response.

Keywords Conscious awareness • Attentional effects • Cued response task • Reaction times • Human

Introduction

Current attention research has been heavily influenced by Posner's cueing paradigm, and associated theoretical models. In the basic effect (Posner et al. 1978), participants were cued with a central directional arrow towards a spatial location where a change in luminance (the 'detection stimulus') would later occur. The directional cues indicated the correct location of the detection stimulus on 80% of trials (valid trials), and indicated the incorrect location on 20% of trials (invalid trials). Participants made a simple keypress response when they detected any luminance change, and their reaction times (RT) were compared with those of a neutral (non-directional) cue condition. Posner and colleagues found an RT benefit of around 25 ms for valid cues and an RT cost of 40 ms for invalid cues, relative to the neutral cue condition. These results have since been widely replicated.

Posner (1980) argued that participants covertly reoriented their attention in the direction given by the cue. Selective attention to the cued location in space was held to influence the neural processes of detection.

Posner (1980) himself argued that attended events enter perceptual awareness with a shorter latency than unattended events, because selective attention filters out unexpected events. He therefore placed the effect prior to stimulus detection, which he defined as:

**Detecting** (meaning) that a stimulus has reached a level of the nervous system at which it is now possible for the subject to report its presence by arbitrary responses that the experimenter may assign. These may be verbal ('I see it') or manual (pressing a key). Detecting means to be aware or conscious of the stimulus (p. 4 in Posner 1980).

Posner's account has remained influential in much subsequent attention research.

However, there is also a 'late filter' view (Deutsch and Deutsch 1963). This second possible locus of selective attention is at the response stage. That is, only one response can be activated at a time. When two choice stimuli are not equally probable, participants pre-prepare the more likely response. This must then be inhibited and replaced when the alternative response is required. A direct test of Posner's detection latency account can be made by measuring the time of conscious awareness of attended and unattended stimuli. Unattended stimuli should be perceived to occur later than attended stimuli. Indeed, such effects have often been reported (e.g.
under the concept of ‘prior entry’ (Titchener 1908). Prior entry may occur when participants divide attention between two or more perceptual streams (Stemberg and Knoll 1973) or between two spatial locations (Abrams and Law 2000).

However, the existence of the prior entry phenomenon has also been disputed. Pashler (1998) argued that multiple stimuli are typically processed in parallel rather than sequentially. Studies of event-related potentials (ERPs) have found some evidence for prior entry in the form of larger P1 and N1 components at lateral and posterior sites when stimuli are attended to (e.g. Mangun and Hillyard 1988). However, other studies (Eimer 1994) have found that these effects are reduced or abolished if subjects are required to respond to unattended as well as attended stimuli. This suggests that these early enhancements are not the cause of RT differences.

Pashler’s alternative suggestion of parallel processing (Pashler 1998) is also in line with current theories in neuroscience. It has been proposed that at least two pathways (ventral and dorsal streams) are involved in the identification of, and response to, visual stimuli (Goodale and Milner 1992; Goodale et al. 1991). A response mediated by one pathway might be speeded or slowed by attentional effects. Detection might use the alternative route, and be unaffected by attention.

An alternative theoretical model, which dissociates motor responses from conscious awareness, comes from the work of Neumann (1990). Neumann suggested that conscious detection of a stimulus does not necessarily influence the response. Direct parameter specification (DPS) was proposed as a way in which a stimulus could elicit a response without having first undergone conscious identification. If a response to a stimulus can occur without conscious detection of the stimulus, then, contrary to the explanation by Posner (1980), a delay in a response is not necessarily due to a delay in detection. Empirical investigations of DPS have established that at least part of the priming effect occurs at the response rather than the detection stage (Neumann and Klotz, 1994). If this is true for a primed stimulus that never reached conscious awareness, it may also be true of a cued stimulus that did.

The standard psychological tool used in most studies investigating attentional effects on perceptual timing is the temporal order judgement (TOJ). However, TOJs cannot straightforwardly be combined with cueing paradigms such as the Posner paradigm. TOJ methods require participants to judge whether the target preceded or followed a reference stimulus (Stemberg and Knoll 1973). The reference stimulus, however, could itself act as an additional attentional cue (Spence and Driver 1994) and could then interfere with the attentional effects being studied. An appropriate measure of perceptual timing in the Posner paradigm requires a timing reference that is not spatially lateralised, that represents a constant attentional load, and that does not itself elicit dynamic reorienting of attention.

We have used the method of Libet et al. (1983) to address these issues. Libet et al. (1983) asked participants to watch a small clock pointer rotating with a period of 2.56 s. Participants used this reference to judge one of a range of internal events, according to condition. These included the perceived times of somatosensory stimuli, of voluntary actions, and of intentions preceding voluntary actions. Libet’s method has been criticised for its dependence on temporal matching across two perceptual streams (e.g. Stamm 1985). Nevertheless, the method appears to yield consistent results across studies (Keller and Heckhausen 1990; Haggard and Magno 1999; Haggard and Eimer 1999). Moreover, any bias in the method due to cross-stream matching, etc should not affect differences between estimates of awareness for the same physical event made in different experimental conditions. Since the Libet clock can be presented at a central fixation point, and rotates continuously throughout each trial, it should not require any dynamic reorienting of attention, though monitoring the clock may represent a constant attentional load.

Problems with the Libet task are well known (e.g. Stamm 1985). However, many of these are avoided by using differences between conditions rather than absolute values. It should also be noted that alternatives to this task (i.e. TOJ) suffer from problems that are at least as bad, if not worse, when used in the context of cueing.

Therefore, we have combined the Posner and Libet paradigms to obtain estimates of time of conscious awareness of internal events in a cued simple response task. Participants observed a rotating clock in central fixation, and made speeded simple responses to lateralised visual stimuli following valid, invalid or neutral central cues. They then reported the clock position at the time of the visual stimulus, or at the time of their response, according to condition. These reports were taken as evidence of time of conscious awareness of corresponding events. Posner’s detection-latency view clearly predicts delayed conscious awareness of stimuli in invalid trials.

Method

Participants

Seven female and five male students of University College London were paid £7.50 each to participate. All were right-handed and had normal or corrected-to-normal eyesight by self-report. Their ages ranged from 23-51 years (mean 29.5). They gave their informed consent to participate in the study, which was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Physiological measurements

The movement of the right index finger to depress a response key was measured by recording the electromyogram (EMG) from the first dorsal interosseus (IDI) muscle of the right hand. Disposable Ag/AgCl surface electrodes (Arbo Inc., Stratford, CT, USA) were used. The EMG signals were amplified, high-pass filtered at 20 Hz.
mains-hum filtered at 50 Hz and digitised at 2.5 kHz. The signals were recorded on a computer for later analysis. The EMG signal was rectified and smoothed using a dual-pass Butterworth filter, with a cut-off frequency of 50 Hz. An algorithm was used to detect EMG onset for each trial. The algorithm used the standard deviation of the EMG signal during a baseline period of 40 ms after target stimulus onset, and before any EMG response occurred, to estimate noise in the EMG signal. The first sample where the EMG signal exceeded 3.97 times this noise level was located. This represents a 2% confidence interval of the normal distribution.

Apparatus and design

All materials were based around replications of the original Libet and Posner paradigms. A clock face was displayed in the centre of a computer screen positioned directly in front of the participant. The clock face was 25 mm in diameter and marked at intervals of 5 'minutes' with numbers from 0 to 55. It subtended a visual angle of 2.14°. A single clock hand 11 mm long was displayed. Its rotation period was 2560 ms.

The cue was presented in the centre of the clock face, prior to the appearance of the clock hand. It could be either neutral '+' or directional '<' or '>', and was presented in size 12 Arial font. It was 4 mm in width and subtended a visual angle of 0.34°.

Two red light-emitting diodes (LEDs) were used as visual stimuli, one on either side of the clock face. They were aligned horizontally with the centre of the clock face at eccentricities of 15° (see Fig. 1). The right index finger was held above the response key, and a simple speeded response was made to the onset of the visual stimuli by briefly pressing the response key. The same response was made regardless of the cue validity or the location of the visual stimuli (i.e. left or right).

Reaction times (RT) were measured in two ways: EMG burst onset (EMG) and the time at which the response button was actually depressed (response time). Judgement errors for each trial were calculated by subtracting the actual time of the judged event from the reported time of that event.

Trials were presented in blocks. A practice block of 12 trials was completed first, followed by seven experimental blocks. The data from practice trials were excluded from all analyses. The first experimental block was always the 'response only' judgement condition. Participants had to fixate the clock and make a speeded response to an LED illuminate. They were asked to attend to the cue that would appear in the centre of the clock on the computer screen, at the start of each trial. This cue would either be neutral '+' or directional '<' or '>'. Following a neutral cue, one of the two LEDs would illuminate with equal probability. A directional cue would be valid (i.e. the indicated LED would illuminate) 80% of the time and invalid 20% of the time (i.e. the opposite LED would illuminate). These conditions allowed the validity effects of expectancy to be considered. Participants were asked to keep their eyes fixated on the clock face but to concentrate their attention on the LED indicated by the directional cue.

At the beginning of the stimulus or movement onset judgement conditions, participants were told to continue to respond as they had before, however, in addition they were asked to verbally report a time indicated by the clock. The time to be reported was either the time at which the LED illuminated (stimulus onset judgement) or the time at which they initiated their response (movement onset judgement), according to condition. Participants were asked to do this whilst keeping their eyes fixated on the clock and directing their attention to the LED indicated by the directional arrow cue.

At the start of each trial the clock hand was blanked and a cue ('<', '>' or '+') was displayed in the centre of the clock face for 350 ms. The cue then disappeared, the clock hand appeared pointing to a random time and began to turn at 2500 ms per rotation. At a random time between 1100 and 1250 ms later, one of the two LEDs was illuminated for 300 ms. The participant responded by pressing the response key with the right index finger, irrespective of the cue or the target location. Each trial lasted for 4350 ms from the cue onset. The clock hand continued to rotate until the trial ended. At the end of the trial the participant gave a verbal report of the clock position at either LED onset or movement onset according to the condition. These were recorded and the data entered later by the experimenter. Participants were encouraged to give as accurate a report as possible, avoiding round numbers and using fractional numbers where possible.

Results

In total, 12.2% of trials were discarded prior to further analysis due to erroneous responses. These comprised 0.83% of trials that were interrupted by the participant, 1.3% of trials in which the participant failed to report a time when requested, 1.6% of trials with multiple responses, 2.5% of trials with pre-emptive responses, and 6% of trials with unanalyseable (noisy) EMG signals. These occurred proportionally across the response and validity conditions.

Figure 2 shows typical (median) EMG data for one participant in the stimulus onset judgement condition.
Fig. 2a, b. Smoothed and rectified EMG signals for one participant in typical trials in the stimulus onset judgement condition. a. Valid cue condition. b. Invalid cue condition. Point 0 on the time axes indicates the light onset in all trials; burst onset/EMG latency is indicated by the dashed line; response keypress is indicated by the dotted line.

Table 1: Means (with SD in parentheses) across participants for EMG latencies and reaction times (RT, milliseconds after stimulus onset) for each judgement and cue type.

<table>
<thead>
<tr>
<th>Cue type</th>
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<tr>
<td></td>
<td></td>
<td>EMG RT</td>
<td>EMG RT</td>
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<td></td>
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<td>276 (82)</td>
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</tr>
<tr>
<td>Invalid</td>
<td></td>
<td>278 (78)</td>
<td>288 (85)</td>
<td>258 (46)</td>
</tr>
</tbody>
</table>

with Fig. 2a showing a typical trial in the valid cue condition, and Fig. 2b showing a typical trial in the invalid cue condition. Note that there is a delay in the EMG latency on the invalid trial (Fig. 2b) relative to the valid trial (Fig. 2a).

Due to unequal condition probabilities (16.6% of all trials had neutral cues and 20% of the directional cues were invalid) mean rather than median averages were used in all analyses (Miller 1988). Two-factor repeated-measures analyses of variance (ANOVA) were conducted on the response time, EMG latency and EMG response size (average EMG height × duration). The factors were judgement type (movement onset, stimulus onset or response only) and cue type (valid, invalid or neutral). The average EMG response size was 27.89 mV s (SD 29.07 mV s). The response size was calculated by taking the area under the rectified and smoothed EMG signal between the burst onset and the release of the response button. The latter is indicated by the end of the data traces in Fig. 2. No significant effects were found for response size across any conditions (all F-values < 1, P > 0.50).

The mean EMG latency and response time for validly cued trials was faster than that for invalidly cued trials (see Table 1). No significant main effect of judgement type was found on EMG latency ($F_{(2,22)}=2.64, P=0.09$) or response time ($F_{(2,22)}=2.94, P=0.07$). A significant main effect was found for cue type (EMG latency $F_{(2,22)}=11.40, P<0.001$; response time $F_{(2,22)}=13.65, P<0.001$). EMG latencies were on average 31 ms earlier in trials with a valid than an invalid cue. EMG latencies for trials with a neutral cue were on average 18 ms later than those with valid cues, and 12 ms earlier than those with invalid trials. Response times for trials with a neutral cue were on average 17 ms later than those with valid cues, and 13 ms earlier than those with invalid trials.

A significant interaction was found between judgement and cue type ($F_{(4,44)}=3.97, P=0.008$; response time $F_{(4,44)}=4.47, P=0.004$) as the Posner effect attenuated in judgement trials. That is, the requirement to judge event times significantly diluted the validity effect. The benefit in valid over invalid trials was smallest when a movement judgement was made (EMG 12 ms, response time 9 ms), larger when a stimulus judgement was made (EMG 29 ms, response time 26 ms) and largest when no judgement was made (EMG 52 ms, response time 54 ms).

Table 2: Means (with SD in parentheses) across participants for stimulus onset judgement errors (reported onset minus stimulus onset, in milliseconds) and movement judgement errors (reported movement onset minus EMG latencies or response times, RT, in milliseconds) for each cue type.

<table>
<thead>
<tr>
<th>Cue type</th>
<th>Judgement type</th>
<th>Movement onset</th>
<th>Stimulus onset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EMG RT</td>
<td>EMG RT</td>
</tr>
<tr>
<td>Valid</td>
<td></td>
<td>-153 (116)</td>
<td>-214 (120)</td>
</tr>
<tr>
<td>Neutral</td>
<td></td>
<td>-152 (131)</td>
<td>-219 (139)</td>
</tr>
<tr>
<td>Invalid</td>
<td></td>
<td>-155 (134)</td>
<td>-210 (134)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Currency</th>
<th></th>
<th>Movement onset</th>
<th>Stimulus onset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EMG RT</td>
<td>EMG RT</td>
</tr>
<tr>
<td>Valid</td>
<td></td>
<td>-261 (261)</td>
<td>-261 (261)</td>
</tr>
<tr>
<td>Neutral</td>
<td></td>
<td>-261 (261)</td>
<td>-261 (261)</td>
</tr>
<tr>
<td>Invalid</td>
<td></td>
<td>-261 (261)</td>
<td>-261 (261)</td>
</tr>
</tbody>
</table>
To investigate perceived time estimates, mean judgement error was calculated for the acceptable trials in each condition. For movement judgements, judgement error was defined as judged time of response minus actual time of EMG onset or actual response time. For stimulus onset judgements, judgement error was defined as judged time of stimulus onset minus actual time of stimulus onset. ANOVAs were conducted on the judgement errors, with factors of judgement type (movement onset or stimulus onset) and cue type (valid, invalid or neutral). Neither judgement error was significantly affected by cue type (see Table 2).

A significant main effect was found for judgement type (EMG $F_{(1,11)}=41.85$, $P<0.001$; response time $F_{(1,11)}=87.45$, $P<0.001$). On average, movements were judged as beginning 153 ms earlier than the EMG onset and 215 ms earlier than the response time. On average, stimuli were judged as occurring 64 ms later than the actual LED illumination. No significant main effect was shown for cue type on judgement error ($F_{(1,22)}=0.5$, $P=0.50$). Most interestingly, no significant interaction was found between judgement error and cue type ($F_{(2.22)}=0.4$, $P=0.70$).

Further planned analyses focused on two specific questions about the validity effect in the stimulus onset judgement condition.

1. Is there a reliable validity effect in conditions also requiring clock based temporal judgements?
2. How do these validity effects enter into awareness: to what extent does attention modulate the perceived timing of a stimulus?

A paired t-test was conducted on the stimulus onset judgement errors for the valid and invalid cue types. No significant effect was found for stimulus onset judgement errors across cue types ($t_{(11)}=1.34$, $P=0.21$). Repeated-measures t-tests were then conducted on the reaction times for the valid and invalid cue type to establish the extent to which significant validity effects were still present within the stimulus onset judgement condition. Significant effects of cue type were found in the stimulus onset judgement conditions (EMG $t_{(11)}=3.79$, $P=0.003$; response time $t_{(11)}=3.53$, $P=0.005$).

To confirm that the validity effect was not entirely accounted for by delayed stimulus awareness, we calculated the differences between the effect of cue validity on RT and its effect on stimulus awareness. This represents the residual amount of the validity effect, which arises after the stage of conscious stimulus detection. This residual validity effect was compared to zero using a t-test. Since cue validity was predicted to benefit RT (i.e. the validity effect is positive) a one-tailed test was used. This test showed a significant residual validity effect occurring after stimulus awareness (EMG $t_{(11)}=-1.82$, $P<0.05$).

A post hoc power analysis of the RT and judgement validity effects showed that whilst five (EMG) or six (response time) subjects would elicit a significant RT effect, 29 subjects would be required for a significant judgement effect.

**Discussion**

This study directly tested the detection-latency account of the Posner (1978) validity effect. In that view, selective attention to stimuli affects reactions to those stimuli because it advances or delays the conscious detection of the stimulus. Here, participants used a continuously rotating clock as a reference against which to judge explicitly the time of stimuli and responses in a Posner task. To our knowledge, this is the first direct test of Posner’s assertion about the relationship between attention and time of awareness.

First, our results replicated the Posner effect. In the no-judgement condition the validity effect, calculated as the difference in RT between invalid and valid trials, was 52 ms (EMG) or 54 ms (response time), and achieved a high level of statistical significance. The validity effect was attenuated when participants used the central clock to judge internal events. In the stimulus onset judgement condition, the validity effect was reduced to 29 ms (EMG) and 26 ms (response time), yet was still highly significant. In the movement onset judgement condition, the validity effect showed the same numerical pattern, but no longer reached conventional levels of significance. This pattern of results suggests that the basic process of attentional selection remained qualitatively similar across conditions. The requirement to monitor the clock did not qualitatively alter the processes of attention. Moreover, a reduced attention effect in the judgement conditions could be predicted by the additional load of monitoring the clock: "The overall effect seems to get smaller as the task is made more difficult" (p. 7 in Posner 1980). We conclude that our use of a Libet clock to measure time of conscious awareness attenuated our attentional effects, but did not fundamentally alter the mechanisms of attention. We find these conclusions unsurprising.

We found no reliable evidence that the time of conscious awareness of invalid stimuli was later than that of valid stimuli, contrary to the detection-latency account of validity effects. When participants explicitly judged the time of stimulus onset, a highly significant validity effect on RT was observed (EMG 29 ms, response time 26 ms). The time of awareness, in contrast, showed only a small 11 ms validity effect, which did not approach statistical significance ($P>0.20$). Moreover, the residual validity effect that could not be explained by detection latencies (i.e. the difference between the validity effects on RT and on time of stimulus awareness) was itself significant ($P<0.05$). These results therefore suggest that detection latency can only account for a relatively small portion of the validity effect. We find it difficult to see how detection-latency accounts of attention can explain our results without ad hoc assumptions. We conclude that the locus of attentional effects does not lie primarily in the time taken for stimuli to reach...
conscious awareness. A numerical argument based on our results would suggest that only 37% of the attentional effect arises prior to stimulus awareness.

We also measured the time of conscious awareness of movement onset in a separate condition. If the locus of the attentional effect was after the time of conscious awareness of movement onset, but before the motor response itself, then any attentional effects on RT, should be accompanied by equal and opposite effects on time of movement awareness. Such a result would imply a very late selection account of attention. This should produce a crossover interaction between condition (valid versus invalid) and measure (RT versus judgement of movement onset). We found no reliable evidence of such an interaction in our data (P>0.70). However, our data showed only small and non-significant validity effects on both RTs (EMG 12 ms, response time 9 ms) and on judgements (~2 ms) in the movement onset judgement condition. We suspect that the absence of a significant validity effect on RT arose because of the high cognitive load of this condition (Posner 1980). Under these circumstances we must remain cautious about the possibility of a late locus for attentional effects. We cannot conclusively exclude the possibility that some proportion of the attentional effect has a locus between the conscious awareness of movement and the onset of muscle activity itself.

Localising attentional effects with respect to time of conscious awareness does not directly relate to traditional ‘early’ or ‘late’ selection models of attention (Lavie 1999). Such models localise attention with respect to cognitive or neural rather than subjective events. Direct comparison of our result with those models would require a clear localisation of conscious awareness of stimulus and response events within traditional cognitive models of attention. To our knowledge, no studies have attempted this, perhaps with good reason. However, previous research based on the Libet paradigm has suggested that awareness of movement onset arises at a stage of premotor processing prior to the final assembly and dispatch of motor commands (Haggard and Magno 1999; Haggard et al. 1999).

It is interesting to relate the present results to the prior entry phenomenon. Prior entry refers to the finding that the onsets of attended events are perceived to occur earlier than the onsets of unattended events (Titchener 1908; Sternberg and Knoll 1973). Prior entry effects are frequently around 50 ms or more in size, and thus provide a plausible mechanism that could underlie the conscious detection account of the Posner effect. Since we found only a small and non-significant attention effect on conscious detection, the present result appears, prima facie, to be inconsistent with the prior entry rule. A re-examination of the prior entry phenomenon, however, has argued that classical experiments purporting to measure prior entry were in fact confounded by response biases (Pashler 1998). One recent study avoided such confounds using an experimental design in which spatial attention and response bias operated in orthogonal directions (Shore et al. 2001). Those authors reported a residual prior entry effect, after removing influences of response bias, of only 12 ms in an endogenous attention paradigm.

Our study, of course, used just one simple response, and therefore avoids response bias confounds, though in a very different way to that of Shore and colleagues. In one sense, therefore, the proportion of the Posner effect in our data that does not enter into conscious awareness (i.e. the perceptual load of attended over an unattended target) may also be taken as a pure measure of the prior entry effect. In our data, this estimate is 11 ms; remarkably similar to Shore and colleague’s estimates based on a very different method. Our method may provide a more direct measure of time of conscious awareness than temporal order judgements used in prior entry studies. For example, when prior entry studies have compared responses to the questions “which stimulus occurred first?” and “which stimulus occurred second?” the resulting perceptual timing estimates have been mutually incompatible (Frey 1990; Shore et al. 2001). This suggests that temporal order judgements are measuring temporal order, and not perceptual timing per se.

Future research might further improve the localisation of these attentional effects. The present data have suggested that validity effects arise largely within the central processing stages occurring between conscious awareness of the stimulus and conscious awareness of the response. Additional research is needed to identify these stages precisely. Clearly, they cannot be the central processes associating stimuli with responses (‘slow route’ of Frith and Done 1986), as the present study required only a simple response. One speculative possibility might be that although the same simple response was required in all conditions, it was prepared as part of an overall action plan including both stimulus and response components (cf. Stoet and Hommel 1999). In the present task, this action plan would be held ready for execution at the required time, and would intrinsically link the expected stimulus to the response. In the event that an unexpected stimulus occurred, the original action plan would have to be first inhibited before a new plan, in response to the new stimulus, could be executed. The time taken to suppress the first plan and initiate the second would correspond to the measured validity effect. Note that the key assumption of this view is that an existing action plan needs to be exchanged for a new one when the trigger stimulus changes, even if the actual motor response does not change.

Alternatively, it may be that the assumption of a series of sequential processing stages is fundamentally flawed. Conscious detection and manual response may be mediated by different neural pathways that process the stimulus independently and in parallel. It is known that manual response times can be affected by priming even when the stimulus never reaches conscious detection (Neumann and Klotz 1994). It may therefore also be the case that conscious detection of the stimulus plays little or no part in the attentional modulation of response latencies because the modulation occurs in a different processing
stream from that subserving conscious detection. If this is the case, further investigations would be required to establish what processing occurs in each stream, and the circumstances under which this processing can slowed or speeded by attentional effects. In future research, we believe that measuring lateralised readiness potentials (LRP) would extend the localisation of attentional effects begun in this paper. Though LRP have been measured in choice response tasks (Miller and Ulrich 1998), they have not previously been measured for simple detection of visual stimuli in a Posner task. We suggest that LRP onset may provide a further landmark internal event for localising attentional effects.

In conclusion, the validity effects seen in the Posner paradigm are not simply caused by delayed conscious detection of unattended targets. They must therefore largely occur either after the stage of conscious target detection or in a separate, parallel processing stream. As the present task did not involve choice responses, the attentional effect cannot be due to overt response selection. However, an action locus of attentional effects remains consistent with our data.

References

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