

Rapid-chase theory:

The influence of the time of invisible stimulus presentation on movement control

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### **Statement of Contribution of Collaborators**

I hereby declare that I am the sole author of this Master's thesis. I collected and analyzed the data for the two experiments presented in this thesis under the supervision of Dr. Erin K. Cressman, who also provided editorial corrections.

Dr. Romeo Chua (Department of Kinesiology, University of British Columbia) helped with the design of the experiments and the analysis of the data.

The article presented in this thesis was co-authored by both Dr. Erin K. Cressman and Dr. Romeo Chua.

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### **Abstract**

In the response priming paradigm, a small briefly presented visual stimulus (i.e., prime) is followed by a larger visible stimulus (i.e., mask) that renders the prime invisible and specifies the target location. According to the rapid-chase theory, the initial portion of the movement is dictated by the prime (initiation criterion) while the later portion is dictated by the mask (takeover criterion) and the prime is initially processed independently from the mask (independence criterion). The purpose of the first experiment was to determine if the processing of the prime and mask fit the predictions of the rapid-chase theory when the prime and mask are presented during an ongoing movement. The second experiment was designed to examine the impact of the prime when it is presented at various times throughout the execution of the movement. Participants initiated rapid pointing movements to a center target. On 1/3 of the trials, participants had to correct their movements to the left (or right) target in response to a left-pointing (or right-pointing) mask arrow, which was preceded by a neutral, left-, or right-pointing prime arrow. In Experiment 1, the prime was presented at movement onset and the mask randomly appeared 33, 50, or 67 ms after prime onset. In Experiment 2, the prime followed movement onset with a delay of 17, 33, or 50 ms and the mask was presented 50 ms after prime onset. In both experiments, participants first modified their movements in the direction indicated by the prime before completing their movements to the correct target in the majority of trials; thus, supporting the initiation and takeover criteria. However, the spatial priming effects did not follow the time course predicted by the independence criterion. Overall, the rapid-chase theory does not seem to apply to movement execution, but the prime is still able to influence the movement despite being presented later in the pointing trajectory.



## **Chapter I: Literature Review**

### **1. Introduction**

The response priming paradigm can be used to examine visuomotor control and allows one to examine the influence of unconscious visual processing on action (Breitmeyer & Ogmen, 2006). A response priming task requires the participant to respond quickly and accurately to a target indicated by a visible (mask) stimulus that was preceded by a briefly presented small (prime) stimulus (Breitmeyer & Ogmen, 2006). In this two stimulus sequence, the mask has a dual function of specifying the required response as well as suppressing the visibility of the prime stimulus through backward masking (Breitmeyer & Ogmen, 2006). In the past, priming studies have been used to examine the influence of the invisible prime on reaction time (RT). Results reveal that the prime can influence RT to the mask and that primes presented before movement onset influence the latency at which the movement is initiated in response to the mask stimulus (T. Schmidt, Niehaus, & Nagel, 2006; T. Schmidt & Schmidt, 2009; T. Schmidt & Seydell, 2008). Moreover, the extent of the influence of the prime stimulus on response initiation has been shown to be modulated by the time between prime onset and mask onset (SOA: stimulus onset asynchrony).

Recently, Cressman and colleagues (2007) have shown that when the prime-mask sequence is presented during a goal directed movement, the prime can take over such that movements are modified in the direction of the prime before being adjusted in the direction of the visible mask. In the current study, we ask if the ability of the prime to influence ongoing movements is influenced by SOA. Thus, the proposed research experiment will manipulate the time between prime and mask onset with respect to movement onset, in order to investigate the influence of invisible stimuli on movement control and determine the time course of online corrections. Research examining movement control in response priming will

increase current knowledge of how rapid movements are controlled and modified and how visual processing and conscious awareness affect ongoing movements. Finally, results will provide insight into whether or not primes and masks are processed in a feedforward manner (based on the initiation, takeover, and independence criteria) as suggested by Schmidt et al. (2006) in his rapid-chase theory. In the present review, current research in motor control pertaining to movement control, consciousness and attention, metacontrast masking, priming effects, and the rapid-chase theory will be presented.

## **2. Movement control**

### *2.1. Movement corrections*

Movement corrections occur often in daily activities without much attention or effort in response to changes in the environment or individual. It has been shown that these corrections can occur unconsciously and automatically (Cressman, Franks, Enns, & Chua, 2006; Day & Lyon, 2000; Johnson, Beers, & Haggard, 2002; Pisella et al., 2000). For example, when targets change locations during saccadic suppression (Bard et al., 1999; Goodale, Pelisson, & Prablanc, 1986; Pélisson, Prablanc, Goodale, & Jeannerod, 1986) or TMS stimulation (Christensen, Kristiansen, Rowe, & Nielsen, 2008; Desmurget et al., 1999), participants are consciously unaware of the target shift, but nevertheless correct their movement to the new target location. In a previous study (Christensen et al., 2008) examining movement corrections without awareness, participants had no difficulty changing the direction of their movement in flight to a new target location even though they were not consciously aware of the onset of the new target location because of TMS interference over the visual cortex. It has also been reported that movements with corrections do not result in slower movement time (MT) compared to movements without corrections (Pélisson et al.,

1986; Pisella, Arzi, & Rossetti, 1998), suggesting that there is no reprogramming of movements when an initial unconscious adjustment is completed (Pélisson et al., 1986).

Not only can movement corrections occur unconsciously in response to unperceived changes in target stimuli, they can also occur in response to visible stimuli. For example, when participants completed an anti-pointing task, which required a movement to a symmetrically opposite location to a visible target shift, they initially pointed in the incorrect direction towards the visible stimulus, despite their intention to move in the opposite direction (Day & Lyon, 2000). As a result, corrections towards the goal location occurred later in anti-pointing trials compared to direct pointing trials, where movements were made directly to the target, as the adjustments required conscious control (Day & Lyon, 2000; Johnson et al., 2002). However, anti-pointing movements resulted in less initial lateral deviations than direct pointing movements indicating that there was some top-down control, reflecting the influence of individuals' intentions and goals on the movement (Day & Lyon, 2000). Furthermore, when asked to reproduce their previous pointing trajectory, participants underestimated the timing and amount of lateral deviation in the direct pointing, but not the anti-pointing task. These results suggest that a supervisory system is activated during anti-pointing trials to suppress initial pointing responses in the direction of the visible target and the activation of this system leads to conscious awareness of the controlled movement (Johnson et al., 2002). In addition, results of the anti-pointing task suggest that two types of movement corrections can occur within the same movement, with the first correction being fast and automatic, and a second being slower and voluntary (Day & Lyon, 2000; Johnson et al., 2002). Recent research has also shown that these automatic corrections can be influenced by the type of task to be completed (Cameron, Cressman, Franks, & Chua, 2009), the

presence of additional target locations (Cameron, Franks, Enns, & Chua, 2007), and by prior experience (Striemer, Yukovsky, & Goodale, 2010).

Unconscious, automatic changes in trajectories in response to a new target location occur quickly. Initial work by Paulignan and colleagues (1991) suggests that movement corrections to a new target can occur in as early as 100 ms as shown by changes to the first peak in the acceleration curve. On the other hand, other studies suggest that modifications to a different target location can result in automatic movement corrections within approximately 125-150 ms (Cressman et al., 2006; Day & Lyon, 2000). Brenner & Smeets (2004) report that 120 ms is enough time to correct a movement to a new target location specified by a coloured target; however, according to Pisella et al. (1998), stopping in response to a colored target takes an additional 80 ms to execute. To summarize, it appears that adjustments in trajectories in response to a new target location can be corrected within approximately 120 ms.

Pisella et al. (2000) suggest that this fast automatic correction of movements depends on processes in the posterior parietal cortex (PPC). The PPC is thought to be involved in movement corrections as it compares sensory (e.g., proprioceptive) feedback to the efference copy (Desmurget et al., 1999). An efference copy, is a copy of the motor commands, used in the detection of errors when the actual feedback of the movement conflicts with the expected feedback (Angel, 1976; Desmurget et al., 1999). Furthermore, the results obtained by Christensen et al. (2008) suggest that participants were using an efference copy since the time to respond to the target perturbation (i.e., correction reaction time (CRT)) was faster than initial RT (i.e., when starting a movement from a stationary position in response to a

stimulus). Once again, suggesting that the movement was not reprogrammed but simply adjusted to the new location.

### **3. Consciousness and attention**

Movement corrections can occur in response to unconsciously perceived stimuli; however, it is debated how certain stimuli reach consciousness and what brain regions are needed to be activated for conscious report.

#### *3.1. Feedforward sweep*

According to the feedforward sweep hypothesis (Lamme & Roelfsema, 2000), recurrent visual processing is required in order for a stimulus to reach consciousness. The visual system is structured in a hierarchical manner and when information is rapidly passed from a lower level brain region to a higher level area, the information is thought to be processed as a feedforward sweep and one does not become aware of the visual information presented (Lamme & Roelfsema, 2000). Recurrent processing occurs when neurons send feedback to other neurons in either the same cortical area or at a lower level based on the information they have previously received from those lower level neurons (Lamme & Roelfsema, 2000; Lamme, 2004). Lamme and Roelfsema (2000) believe that visual awareness is only possible when there is recurrent feedback, and thus an initial fast feedforward sweep is insufficient to cause conscious perception. On the other hand, Goodale and Milner (1992) believe that consciousness arises from ventral stream processing, which includes information passing from early visual areas to the inferior temporal cortex. In contrast, dorsal stream processing, which can occur unconsciously according to Goodale and Milner (1992), results in fast, automatic movement corrections as discussed above (see 2.1. Movement corrections). The dorsal stream, which passes information from early visual areas

to the posterior parietal cortex, is responsible for interacting with objects and has a faster feedforward sweep compared to the ventral stream, which is responsible for object identification (Goodale & Milner, 1992; Lamme & Roelfsema, 2000).

The distinction between feedforward and recurrent processing provides an account for how stimuli can be presented such that they are not consciously perceived. For example, in the response priming paradigm that will be discussed in more detail below (see 4. Metacontrast masking), when stimuli are displayed in rapid succession, the presentation of the second (mask) stimulus can lead to the first (prime) stimulus being prevented from accessing conscious awareness. Specifically, when a prime is presented it initiates a feedforward sweep of activation within the visual system, but the recurrent activity associated with the prime stimulus cannot be completed since the feedforward sweep associated with the mask stimulus is activated. Consequently, neurons receive mixed signals since information about the mask comes from lower brain regions and information about the prime comes from higher brain regions (Lamme & Roelfsema, 2000).

### *3.2. A model incorporating consciousness and attention*

According to William James (1890) (as cited in R. A. Schmidt & Lee, 2011) attention is, “the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others.” (pp. 403-404). In other words, attention is a limited resource since only a restricted amount of items can be kept in focus. Attention is also required to properly store information related to a stimulus in memory in order to successfully retrieve and report it later on. Although the concepts of attention and consciousness are separate, they are

closely related. For example, only an attended stimulus can lead to a correct conscious report of the stimulus and attention allows stimuli to be processed faster than unattended stimuli (Lamme, 2004). Lamme (2004) provides a useful model for defining consciousness and how it relates to attention.

According to Lamme (2004), there exist four different relationships between consciousness and attention: attended-conscious, unattended-conscious, unattended-unconscious, and attended-unconscious. When an attended stimulus reaches consciousness, the result is termed access awareness. In contrast, phenomenal awareness occurs when an unattended stimulus reaches a conscious level. Phenomenal awareness is when there is local recurrent processing within visual areas whereas access awareness is when there is widespread recurrent processing throughout the brain (Lamme, 2004). Lamme's (2004) definition of phenomenal awareness is similar to Dehaene, Changeux, Naccache, Sackur, & Sergent's (2006) less stringent definition of preconscious processing, since neither one results in conscious report unless additional attention is focused on the stimulus, making preconscious and phenomenal awareness an intermediate stage between unconscious and conscious processing. Furthermore, stimuli can be unconscious and unattended but it is uncertain what affect these stimuli have on behaviour. Finally, response priming as discussed below (see 4. Metacontrast masking), is an example of an attended-unconscious relationship because attention is directed to the stimulus and yet the stimulus does not reach consciousness. In this case, the prime stimulus cannot be correctly identified but still influences behaviour.

#### **4. Metacontrast masking**

The unconscious processing of visual information and the resulting automatic movement corrections can be studied using the response priming paradigm. As previously mentioned (see 1. Introduction), in a two stimulus sequence, participants are instructed to make a response, usually a key press or a reach, based on a feature of the second stimulus, known as the mask. A prime stimulus precedes the mask stimulus but is prevented from accessing conscious awareness (i.e. “masked”) by the mask through metacontrast masking. Metacontrast masking is a type of backward masking by structure because the inner contour of the mask is similar to the outer contour of the prime, and therefore the mask resembles the prime with respect to a specific characteristic such as the orientation or curvature of lines (Breitmeyer & Ogmen, 2006). An example of a metacontrast masking stimulus sequence is a right-pointing arrow prime followed by a larger right-pointing arrow mask (see Figure 1 in Methods). In metacontrast masking, the congruency, also referred to as the compatibility, of the prime-mask pair on performance is typically examined. The prime-mask pair is considered congruent (see Figure 1 in Methods) when the prime and mask specify the same response because they share a very specific characteristic such as colour or shape (e.g., right-pointing arrows), which participants are instructed to respond to. When the prime and mask indicate different responses (e.g., left-pointing arrow prime and right-pointing arrow mask), the prime-mask pair is incongruent, and when the prime is neutral, meaning it does not specify a response, the prime-mask pair is neutral (see Figure 1 in Methods).

#### **5. Priming effects on performance**

In response priming tasks, even though the prime is not perceived at a conscious level, it exerts an influence on behaviour. Typical studies have displayed the prime-mask



sequence in a RT paradigm and instructed participants to press a key depending on the identity of the mask (e.g., to press a right key in response to a right arrow and a left key in response to a left arrow). The findings indicate that error rates and RTs are affected by the congruency of the prime-mask pair (Breitmeyer, Ogmen, & Chen, 2004; T. Schmidt, 2002; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). In general, when the prime-mask pair is congruent, RTs to the mask are faster than if the prime-mask pair is incongruent (Vorberg et al., 2003). The difference in RT between the incongruent trials and congruent trials is referred to as the priming effect. In addition to RT, error rates can also be used to examine the priming effect. Typically, more errors are committed in incongruent trials and as the prime-mask SOA increases (Vorberg et al., 2003).

Several factors influence the overall priming effect such as expertise (Kiesel, Kunde, Pohl, Berner, & Hoffmann, 2009), task instructions (Neumann & Klotz, 1994; Schlaghecken & Eimer, 2004), probability of stimulus presentation (Cheesman & Merikle, 1986; Cressman, Lam, Franks, Enns, & Chua, 2013), and stimuli characteristics (Breitmeyer & Ogmen, 2006). In addition, a major factor influencing the priming effect is the time between prime-mask onset (stimulus onset asynchrony (SOA)). The importance of the SOA has been expressed by various authors (Kahneman, 1967; F. Schmidt, Haberkamp, & Schmidt, 2011). Recently, F. Schmidt et al. (2011) stated, “The most prominent and influential variable in response priming experiments is the SOA” (p. 123).

In general, as the SOA increases, the RT in congruent trials decreases and the RT in incongruent trials increases, resulting in an overall increase in the priming effect (T. Schmidt et al., 2006; Vorberg et al., 2003). Interestingly, even when longer duration primes were

followed by shorter duration masks, resulting in better prime identification, similar priming effects to the less visible prime condition were observed (Vorberg et al., 2003).

### *5.1 Movement corrections in response priming*

Response priming paradigms have also been used to examine unconscious online movement corrections in response to a congruent, neutral, or incongruent prime-mask pair (Cressman, Franks, Enns, & Chua, 2007). In this task, participants were instructed to point to a center target. However, on 25% of the trials a left or right arrow mask appeared after movement onset, requiring a response to the left or right target location, respectively. Results showed that participants' movements deviated towards the target location indicated by the prime stimulus. In other words, participants started to adjust their movements earlier in congruent trials or to the incorrect target location during incongruent trials. Movement corrections in response to prime onset occurred within 277 ms and corrections in response to the mask stimulus occurred approximately 56 ms later, a time that equaled the prime-mask SOA. Thus, using this task, it is possible to further examine unconscious, automatic movement adjustments and the time required to make these fast adjustments in response to invisible and visible stimuli.

### *5.2. Prime visibility*

The prime's ability to influence performance, as discussed above (see 5. Priming effects on performance), occurs despite the fact that the prime is "invisible" to participants. Complete masking is achieved when participants are unable to identify the prime above chance levels and no masking occurs when participants are able to correctly identify the prime with close to 100% accuracy (F. Schmidt et al., 2011). When the prime is only correctly identified between 50% and 100% of the time, the prime is partially visible and the

observed priming function depends on stimulus characteristics such as duration, intensity, and contrast (Breitmeyer & Ogmen, 2006). When assessing whether or not the primes can be correctly identified within a metacontrast masking paradigm, different priming functions can be observed. Type A masking is when prime visibility increases linearly as the time between prime-mask onset (SOA) increases (Breitmeyer & Ogmen, 2006; F. Schmidt et al., 2011). Type B masking is when the prime is perceived better at short and long SOAs but is poorly identified at middle SOAs (approximately 50 ms) giving the visibility function a “U” shaped curve (F. Schmidt et al., 2011). There exists individual variability when assessing prime visibility as some people are able to perceive the prime above chance levels regardless of SOA, while others are not (Breitmeyer, Ro, Ogmen, & Todd, 2007). Similarly, some individuals tend to be type A observers while others are type B observers (Albrecht, Klapötke, & Mattler, 2010; Albrecht & Mattler, 2012). As a result, the SOA that optimally reduces prime visibility is different for everyone, but in general primes are typically rendered invisible when the prime-mask SOA is approximately 50 – 60 ms (Breitmeyer, Ogmen, et al., 2004; Breitmeyer, Ogmen, Ramon, & Chen, 2005; Breitmeyer et al., 2007; Cressman et al., 2007; Tapia, Breitmeyer, & Shooner, 2010).

Several studies (Breitmeyer, Ogmen, et al., 2004; Breitmeyer, Ro, & Singhal, 2004; Finkbeiner & Friedman, 2011; Frings & Wentura, 2008) excluded data obtained from participants who correctly identified primes above chance levels from further analysis, but other researchers (F. Schmidt et al., 2011) believe this is not required because there exists a double dissociation between prime visibility and priming effects, the difference in RT between incongruent and congruent trials. As outlined above (see 5. Priming effects on performance), the prime influences performance such that RT in congruent trials is faster

than RT in incongruent trials, regardless of prime visibility. RT is slower in incongruent trials because the unconsciously perceived prime stimulus activates a response that is contrary to the individual's intentions; thus, requiring additional time to respond to the correct mask stimulus. As shown by Vorberg and colleagues (2003), increasing priming effects were observed for both type A and type B masking. In other words, even when prime visibility followed a type B function, where prime visibility initially decreased as SOA increased, the priming effect still increased, suggesting priming effects do not depend on conscious perception (Vorberg et al., 2003).

Primes that surpass the threshold level needed for visibility are supraliminal while subliminal primes are stimuli that do not attain the required threshold for conscious report (Dehaene et al., 2006). The ideal method to use when determining prime visibility is debatable. According to Cheesman & Merikle (1986), "consciousness is a subjective state" (p.344) and therefore subjective measures (e.g., confidence ratings) should be used instead of objective measures (e.g., forced-choice discrimination) to determine prime awareness. In contrast, recent studies have used forced-choice objective measures (Cressman et al., 2007; Schlaghecken & Eimer, 2004; F. Schmidt & Schmidt, 2010). F. Schmidt et al. (2011) suggest using subjective measures in conjunction with objective measures. Furthermore, they suggest conducting trials to assess prime visibility in a separate block of trials after having completed the block of mask identification or mask pointing trials since determining prime visibility immediately after a trial in which participants responded to the mask stimulus requires the participant to divide their attention between the two different tasks (F. Schmidt et al., 2011). Since attention is a limited resource and only attended stimuli can be consciously reported (Lamme, 2004), it is important to assess prime and mask visibility separately. However,

Lamme (2004) cautions that people's conscious report of visual awareness does not always reflect their sensory experience since the verbal report can depend on attention and working memory.

## **6. Rapid-chase theory**

Conscious awareness and behaviour associated with a prime stimulus can be dissociated; consequently, Schmidt et al. (2006) listed three criteria that can be used to determine if the processing of the invisible stimulus proceeds in a feedforward fashion based on the impact of the prime on behaviour. Schmidt et al. (2006) examined differences in priming effects in metacontrast masking paradigms with different mask strengths, SOAs, and stimulus contrasts. Masks were either strong, the inner contour of the mask was fitted to the outer contour of the prime, or weak, a space separated the outer contour of the prime and the inner contour of the mask. Contrast was manipulated by varying the luminance of the stimulus. The task required participants to point as fast as possible to a green or red target that appeared simultaneously in opposite quadrants. Overall, response priming effects were stronger when a weak mask was used, the SOA increased, and prime-mask contrast was high (T. Schmidt et al., 2006). Although mask strength, SOA, and contrast influenced the overall response priming effects, mask strength and SOA did not influence the participants' early pointing trajectories, indicating that the priming effects were time locked to prime onset and were initially independent of the mask properties. Based on these results, Schmidt and colleagues proposed their rapid-chase theory. The rapid-chase theory outlines criteria for establishing if visual information is processed in an unconscious and feedforward manner, based on the individual's motor behaviour (T. Schmidt & Schmidt, 2009; T. Schmidt et al., 2011, 2006; Vath & Schmidt, 2007). The rapid-chase theory incorporates ideas from other

theories related to unconscious processing of visual information such as the feedforward sweep (Lamme & Roelfsema, 2000) and direct parameter specification (DPS; Neumann & Klotz, 1994; Neumann, 1990).

As discussed above (see 3. Consciousness and attention), the feedforward sweep is the rapid processing of visual information where lower level cortical areas rapidly project information to higher brain regions (Lamme & Roelfsema, 2000). However, it is only when there is recurrent feedback that a stimulus reaches consciousness. DPS (Neumann & Klotz, 1994; Neumann, 1990) states that a stimulus feature can directly activate an associated motor response without the person being aware of its occurrence if it is relevant to the task. In other words, there exists a dissociation between awareness and motor behaviour.

#### *6.1. The rapid-chase criteria*

The three criteria outlined in the rapid-chase theory (T. Schmidt & Schmidt, 2009; T. Schmidt et al., 2011, 2006; Vath & Schmidt, 2007) are the following:

1. Initiation criterion: the prime influences the onset and initial direction of the corresponding response
2. Takeover criterion: the mask influences the movement before it is completed
3. Independence criterion: the initial movement kinematics depend only on the information provided by the prime and are not influenced by the properties of the mask

The initiation criterion is important as it ensures that the beginning of the movement is influenced by the prime stimulus, while the takeover criterion ensures that the mask stimulus is not ignored, but eventually influences the response (T. Schmidt et al., 2011). Together, the initiation and takeover criteria ensure that the prime influences motor output

and then that the mask chases the prime fast enough so it can affect the movement before the incorrect response is completed (T. Schmidt & Schmidt, 2009; Vath & Schmidt, 2007). The independence criterion makes sure that the two stimuli are processed in strict sequence and that the pertinent features of the prime and mask remain separate (i.e., not integrated into a composite stimulus) (Vath & Schmidt, 2007). Consequently, if the independence criterion is not met this means that the information carried by the prime and mask are integrated (Vath & Schmidt, 2007). For instance, when the SOA between the prime and mask is too short ( $< 30$  ms), the prime and mask stimuli are integrated and create an ambiguous stimulus resulting in a movement delay, and therefore, the independence criterion is not met (T. Schmidt et al., 2006). Similar to the rapid-chase theory, VanRullen & Koch (2003) argue that in order to show that a system operates in a feedforward manner it is necessary to examine the time course of the system's inputs and outputs to show that the first stimulus is processed without any interference from the second stimulus. Any stimuli integration or interference would affect the final outcome of the response.

In contrast to the feedforward sweep model, the rapid-chase theory does not require a strict feedforward processing at all levels, but requires the system to behave like a feedforward system; thus it allows some local recurrent processing to occur (T. Schmidt & Schmidt, 2009; T. Schmidt & Seydell, 2008; T. Schmidt et al., 2011). Note that according to Lamme (2004), this local recurrent processing would result in phenomenal awareness.

According to Neumann's direct parameter specification theory, the prime directly activates the movement, based on the participants' intentions, without the need for cognitive interventions (Neumann & Klotz, 1994; Neumann, 1990). Interestingly, similar to the rapid-chase theory, Neumann and Klotz (1994) further suggested that the prime and mask are

racing against each other. However, they go on to suggest that the final outcome of the movement could be influenced by the prime or mask, as it is the stimulus that wins the race that leads to its assigned response and ultimately determines the final outcome of the movement and associated RT.

### *6.2. Evidence supporting the rapid-chase theory*

Evidence for the rapid-chase theory comes from behavioural studies using backward metacontrast masking and neuroimaging techniques such as electroencephalogram (EEG), functional magnetic resonance imaging (fMRI), and transcranial magnetic stimulation (TMS).

#### *6.2.1. Behavioural studies*

As outlined above (see 5. Priming effects on performance) many studies (Breitmeyer, Ogmen, et al., 2004; Cressman et al., 2007; Vorberg et al., 2003) have observed faster RTs in congruent trials independent of prime awareness. Most of the evidence for the rapid-chase theory comes from behavioural studies that employed a metacontrast masking paradigm to investigate the temporal processing of the prime and mask stimuli. Specifically, early evidence for the rapid-chase theory comes from examining spatial trajectories in studies requiring the participant to initiate their pointing response to one of two colour targets that would appear simultaneously in opposite quadrants (T. Schmidt et al., 2006; T. Schmidt, 2002). Additional evidence for the rapid-chase theory comes from studies that have examined priming effects when categorizing natural and unnatural pictures and when pointing to targets based on their shape (T. Schmidt & Schmidt, 2009). Evidence also comes from studies where the target stimulus was cued by a color or shape stimulus (F. Schmidt & Schmidt, 2010) or by a spatial cue (T. Schmidt & Seydell, 2008).



The spatial pointing trajectories obtained in these studies indicated that the prime initially influenced the direction of the finger because the finger started its movement based on the prime's characteristics. As a result, the finger moved in the incorrect direction in incongruent trials, which supports the initiation criterion. However, after a time period dependent on the prime-mask SOA, participants adjusted their movements to the correct target indicated by the mask; thus, providing evidence for the takeover criterion. Furthermore, the initial pointing trajectories were identical for all SOAs because only the prime had been processed and influenced the movement. This is further highlighted when examining the spatial priming effects (i.e., the difference between the spatial pointing trajectories of incongruent and congruent trials), as the initial time course of the spatial priming effect was independent of the SOA or the mask characteristics as predicted by the independence criterion. Only after the mask took over the movement did the spatial priming functions differ from one another at different SOAs.

#### 6.2.2. Neuroimaging studies

While behavioural studies have shown a dissociation between motor performance and awareness, the temporal processing and the brain regions involved in this dissociation have been studied using neuroimaging techniques to determine the underlying brain activity responsible for the observed behavioural effects in priming tasks. Moreover, results from neuroimaging techniques using EEG, fMRI, and TMS can be used in conjunction with behavioural paradigms to provide further support for visual processing theories, specifically the rapid-chase theory.

#### 6.2.2.1. Electroencephalogram (EEG)

EEG records the electrical activity of neurons and has a high temporal resolution, within milliseconds (Gevins, Leong, Smith, Le, & Du, 1995; Haynes & Rees, 2006). RT studies employing EEG have found that the prime influences motor preparation, such that it can directly activate its associated response without conscious awareness (Coles, 1989; Dehaene et al., 1998; Eimer & Schlaghecken, 1998; Vath & Schmidt, 2007). Thus, these studies provide evidence for direct parameter specification and the rapid-chase theory. The prime initially activated the response in the correct direction in congruent trials, but activated the incorrect response in incongruent trials. Specifically, an observable difference between the lateralized readiness potential (LRP) signal in congruent and incongruent conditions occurred around 200 ms after prime onset (Eimer & Schlaghecken, 1998; Vath & Schmidt, 2007). The LRP is the difference in cortical activity recorded between the motor cortex representations of the left and right hands and reflects the covert initial activation of the correct or incorrect response depending on the positive or negative deflection of the signal (Coles, 1989, Eimer, 1998). Vath and Schmidt (2007) used EEG to examine the time-course of the LRP associated with the prime and mask. They varied the prime-mask SOA between 30, 60, and 90 ms and found that the amount of time the LRP in incongruent trials deviated towards the incorrect response was dependent on the length of the SOA. With a longer SOA, the incorrect response was activated for a greater duration. The priming lateralized readiness potentials (PLRPs), LRPs in congruent trials minus LRPs in incongruent trials, revealed that the early phase reflected prime onset while the later phase reflected mask onset. Overall, the results from this study provide additional support for the rapid-chase theory as they satisfy the initiation and takeover criteria. In particular, the prime influenced the early response

preparation and the mask influenced the later portion. Furthermore, the initial activation was independent of the mask's onset and colour saturation (an index of signal strength), satisfying the third rapid-chase criterion. The studies by Dehaene et al. (1998) and Eimer & Schlaghecken (1998) also provide evidence for the initiation criterion of the rapid-chase theory and DPS because, in incongruent trials, the early phase of the LRP signal reflected the incorrect response which was activated by the prime stimulus. Moreover, participants were able to successfully complete most trials, meaning the mask eventually influenced the response before the movement had finished, providing evidence for the takeover criterion of the rapid-chase theory.

#### 6.2.2.2. Functional magnetic resonance imaging (fMRI)

fMRI records blood oxygenation and can be used to determine the brain regions activated during a task, since greater neuronal activity results in an increase in local oxygenated blood (Matthews & Jezzard, 2004). In contrast to EEG, fMRI has poor temporal resolution, but high spatial resolution (Matthews & Jezzard, 2004). In a semantic priming task using fMRI, participants were required to determine if the target, presented in either Arabic or written format, was smaller or greater than the number five by pressing a left or right key, respectively (Dehaene et al., 1998). fMRI results indicated that the prime activated the motor cortex of the hemisphere contralateral to the hand that would be required to complete the task. In other words, in the incongruent trials the prime activated the motor areas associated with the incorrect response. The primes activated a response without being consciously perceived as expected from the rapid-chase theory (T. Schmidt et al., 2006) and as outlined in Neumann's DPS model (Neumann & Klotz, 1994; Neumann, 1990).

#### 6.2.2.3. Transcranial magnetic stimulation (TMS)

TMS is a technique that allows researchers to enhance or disrupt the normal functioning of the human brain by interfering with neuron activity (Pascual-Leone, Walsh, & Rothwell, 2000). Evidence for the visual system operating as a feedforward system comes from TMS studies using a metacontrast masking task (Ro, Breitmeyer, Burton, Singhal, & Lane, 2003), supraliminal priming task (Sack, van der Mark, Schuhmann, Schwarzbach, & Goebel, 2009), and a phosphine motion perception task (Pascual-Leone & Walsh, 2001). The findings of these studies indicate that visual awareness is dependent on feedback connections providing support for the feedforward sweep hypothesis, an assumption of the rapid-chase theory, which states consciousness can only arise from recurrent feedback processing (Lamme & Roelfsema, 2000). Furthermore, when the prime stimulus was presented below fixation, there was an increase in RT in congruent trials when TMS was applied 60, 80, and 100 ms after prime onset, but RT decreased in incongruent trials when TMS was applied at 80 ms (Sack et al., 2009). These results suggest that TMS interrupted the processing of the prime stimulus and, as a result, the prime was unable to successfully activate its associated response leading to a decrease in the observed priming effects between 60 – 100 ms after prime onset. Thus, the observed behavioural outcomes did not follow the initiation criterion of the rapid-chase theory because TMS interfered with the prime's ability to directly activate a response, as predicted by DPS. In comparison, the typical priming effect was observed in trials with no TMS, suggesting that the prime was able to influence the movement in trials without TMS, as outlined by the rapid-chase theory.

### *6.3. Limitations of the rapid-chase theory*

There are certain limitations of the rapid-chase theory. Given limitations in behavioural and neuroimaging recording, it is not possible to determine whether or not visual information is processed in a strict feedforward manner. Results can only be used to determine if the system as a whole acts in a feedforward manner (T. Schmidt & Schmidt, 2009). The rapid-chase theory breaks down at really short prime-mask SOAs (<30 ms), since characteristics of the prime and mask are integrated and influence the initial response (T. Schmidt et al., 2006). The processing of the prime and mask at these short SOAs may exceed the temporal resolution required by the feedforward sweep in order to keep the stimuli as separate events (T. Schmidt et al., 2006).

Moreover, the rapid-chase theory only accounts for behaviour in response to a two stimulus sequence (T. Schmidt & Schmidt, 2009). For example, priming effects tend to break down when a cue is added to the stimulus sequence at short cue-prime intervals (250 ms; Neumann & Klotz, 1994). In this task, participants responded to the mask box that was flanked on the top and bottom by a smaller filled box, but the stimulus-response compatibility of the task could change every trial. Consequently, a cue presented 250, 750, or 1250 ms prior to prime onset indicated the stimulus-response relationship of the upcoming trial. A filled square indicated a compatible condition and an open square indicated an incompatible condition. It is thought that the priming effect was reduced when the cue, which provided relevant information for the successful completion of the task, was presented 250 ms before the prime because there was not enough time to complete the planning of the action without additional conscious processing. Since a criterion of the rapid-chase theory is that the prime directly activates a response, the rapid-chase theory breaks down at short cue-

prime intervals. As a result, if a third (cue) stimulus is added to the prime-mask sequence, enough time must elapse between cue onset and prime onset to allow the participant to integrate the information provided by the cue into the motor program in order for the prime to directly influence the movement.

Additionally, depending on task instructions, processing of the prime and mask may not follow the rapid-chase theory when having to classify images. For example, when participants had to point to the largest figure in real life when presented with a picture of an object and an animal as the primes and masks, the behavioural responses did not abide by the rapid-chase theory. The independence criterion was not followed because the initial response was not independent of the prime-mask SOA, indicating that the mask influenced the response. However, primes were successful in delaying movement onset in incongruent trials. In contrast, when participants were asked to classify the same pictures based on the presence of an animal or an object, instead of their relative size, responses respected the rapid-chase criteria. The prime initially influenced movement onset, and participants were able to successfully point to the correct target in incongruent trials (T. Schmidt & Schmidt, 2009). Based on these results, the authors speculate that image classification based on size requires more cognitive control or more recurrent processing, resulting in conscious processing, and therefore, does not satisfy the rapid-chase theory (T. Schmidt & Schmidt, 2009). Another instance that requires recurrent processing to produce an unconscious response is when distracting stimuli partially occlude the task relevant characteristics of the prime preventing the prime from being processed by a single feedforward sweep (F. Schmidt, Weber, & Schmidt, 2014). Additional feedback projections are necessary to distinguish the relevant features of the prime stimulus in order to activate a response.

It is unknown whether or not the rapid-chase criteria can be applied to ongoing movements since most priming studies typically present the prime before movement onset, and examine the prime's influences on initial motor responses. As outlined above (see 5.1 Movement corrections in response priming), Cressman and colleagues (2007) observed a priming effect for subliminal shapes presented after movement onset and found that arrows did in fact influence the control of ongoing movements. Similarly, Fukui & Gomi (2012) found that primes had an influence on movement even when they were presented 100 ms after movement onset. Nonetheless, in both studies the SOA was kept constant limiting the ability to determine whether or not responses conformed to the independence criterion of the rapid-chase theory. It is possible that movements are corrected differently when a perturbation occurs after movement onset than before movement onset since the time required to respond to a target perturbation during flight has been shown to be quicker than initiating a response to a target suggesting movements may be mechanically easier to correct during flight than during initiation (Christensen et al., 2008). Additionally, online movement corrections may differ from movement corrections during initiation because the dorsal stream may be more engaged during ongoing movements (Milner & Goodale, 1995, 2008) or the threshold needed to be attained by the prime in order to activate a response may be lowered during flight (Cressman et al., 2007). Thus, the influence of the prime-mask SOA during movement is unknown and requires further investigation to determine if the behavioural output abides by the independence criterion as outlined by the rapid-chase theory. Similarly, no studies have varied the time interval between movement onset and prime onset to examine how this delay impacts movement corrections.

## **7. Objectives**

Overall, movements can be corrected unconsciously and automatically in response to visual stimuli. Furthermore, behavioural and neuroimaging studies presenting visual stimuli unconsciously support the rapid-chase theory as it pertains to movement initiation. Nevertheless, to extend the rapid-chase theory to movement execution, movement corrections to primes that are presented after movement onset must be examined.

The response priming paradigm is well suited to examine automatic, unconscious online corrections as the prime stimuli are processed unconsciously. As well, the stimulus sequence can be presented during ongoing movements, resulting in deviations towards the incorrect target if the prime takes over control of the movement on incongruent trials.

The first purpose of the study is to examine the effect of varying SOA on the control of ongoing movements to determine the time course of unconscious processing of visual information during movement execution. According to the rapid-chase theory, the initial spatial priming effects should be time-locked to prime onset and only after a time period dependent on the prime-mask SOA will the mask start to influence the movement (T. Schmidt & Schmidt, 2009). Thus, it is hypothesized based on the rapid-chase theory that the time required to make final adjustments will be dictated by the time of the SOA. In other words, it is predicted that corrections in the congruent trials will be faster than corrections in the neutral and incongruent trials to the mask and this difference will increase with an increase in SOA. If the results obtained confirm this hypothesis then the results would provide evidence that the visual system initially operates in a feedforward manner during the correction of movements; thus, extending the rapid-chase theory to movement execution. On the other hand, if the pointing trajectories do not abide by the rapid-chase theory, this does



not necessarily indicate that the prime and mask are processed as a single stimulus but that the observed behaviour cannot be used as evidence of the prime triggering an initial feedforward sweep that is independent and separate from the processing of the mask. The second purpose of the proposed experiment is to manipulate the time between movement onset and prime onset to determine whether primes exert a greater influence at certain time points in the movement. It is hypothesized that movement deviations to the target will occur later as the time between movement onset and prime onset increases but that the priming effects will be similar because the prime-mask SOA is constant. This would suggest that primes exert a similar influence during movement regardless of their onset time.

## **Chapter II: Research Article**

# **The rapid-chase theory does not extend to movement execution**

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**Abstract** It is assumed that the processing of an invisible (prime) stimulus followed by a larger visible (mask) stimulus occurs sequentially in a feedforward manner when the three criteria outlined by the rapid-chase theory are met. Specifically, the initial portion of the movement is dictated by the prime (initiation criterion) while the later portion is dictated by the mask (takeover criterion). Furthermore, the processing of the prime is initially independent from the properties of the mask (independence criterion). The rapid-chase theory has been supported by movement initiation studies but has yet to be examined with respect to movement execution. Processes underlying movement execution might differ from movement initiation because of an increased involvement of the dorsal stream or a decreased prime activation threshold when executing a response. The purpose of the current study was to determine if the processing of the prime and mask fit the predictions of the rapid-chase theory when the prime and mask are presented during an ongoing movement. In two experiments, participants made rapid pointing movements to a center target flanked by a left and right target. On 1/3 of the trials, participants had to correct their movements in response to a left or right-pointing mask arrow. The mask was preceded by a neutral, left-, or right-pointing prime arrow. In Experiment 1, the prime was presented at movement onset and the prime-mask stimulus onset asynchrony (SOA) was manipulated between 33, 50, and 67 ms. In Experiment 2, the prime followed movement onset with a delay of 17, 33, or 50 ms and the prime-mask SOA was constant at 50 ms. Although in both experiments the results support the initiation and takeover criteria of the rapid-chase theory, the data did not support the independence criterion, such that the spatial priming effects did not follow the expected time course if the prime was initially processed independently from the mask. Consequently, the rapid-chase theory does not appear to extend to movement execution.

**Keywords:** Response priming, Movement corrections, Unconscious processing, Rapid-chase theory, Prime-mask SOA

## **Introduction**

In many daily activities, online movement corrections are necessary to successfully perform an intended goal-directed action. Movement corrections can occur online due to changes in task goals or the presence of additional information. Furthermore, movement corrections can occur automatically and unconsciously in response to visual stimuli as evidenced by the anti-pointing (Day & Lyon, 2000; Johnson, Beers, & Haggard, 2002) and the double-step paradigms (Bard et al., 1999; Goodale, Pelisson, & Prablanc, 1986; Pélisson, Prablanc, Goodale, & Jeannerod, 1986).

With advances in technology, it has become easier to use pointing tasks, instead of discrete tasks (e.g., reaction time (RT) tasks) to gain a better understanding of movement corrections as well as the cognitive events that underlie corresponding decision making processes (Song & Nakayama, 2009). Specifically, the analysis of pointing trajectories allows for real-time observation of the control processes leading to the successful completion of the task. This advantage has made pointing movements a valuable tool in the investigation of invisible stimuli on behaviour (Cressman, Franks, Enns, & Chua, 2007; Cressman, Lam, Franks, Enns, & Chua, 2013; Finkbeiner & Friedman, 2011; Finkbeiner, Song, Nakayama, & Caramazza, 2008; Fukui & Gomi, 2012; Ocampo & Finkbeiner, 2013; T. Schmidt, Niehaus, & Nagel, 2006; Xiao & Yamauchi, 2014). In these studies, participants pointed as fast and as accurately as possible in response to a visible stimulus. Unbeknownst to the participants, a briefly presented smaller stimulus (i.e., prime) preceded the larger stimulus and the two stimuli shared task relevant characteristics. Although these studies differed with respect to such experimental manipulations as the type of masking that was used (i.e., metacontrast or pattern masking), the number of stimuli in the sequence, the distance of the targets, and the

onset of the prime relative to movement onset, in all cases, participants remained unaware of the prime and the prime still influenced their behaviour.

These results are in agreement with traditional prime-masking studies, which have typically used a RT task to investigate unconscious processing. In a prime-mask RT task, the mask has the dual function of suppressing the visibility of the prime in addition to specifying the required response. Initial investigations using RT tasks have shown that when the prime and mask are congruent (i.e., they specify the same response), RTs are faster than when the prime is neutral (i.e., it does not specify a response) or the prime and mask are incongruent (i.e., they indicate opposite responses) (Klotz & Wolff, 1995; Neumann & Klotz, 1994; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). The priming effect, defined as the difference between incongruent and congruent conditions with respect to a specific performance variable (e.g., RT, movement time (MT) or errors), is a measure of the impact of the prime on behaviour. Several factors have been shown to influence the overall priming effect, including participant expertise (Kiesel, Kunde, Pohl, Berner, & Hoffmann, 2009), task instructions (Neumann & Klotz, 1994; Schlaghecken & Eimer, 2004), probability of stimulus presentation (Cheesman & Merikle, 1986; Cressman et al., 2013), and stimuli characteristics (Breitmeyer & Ogmen, 2006). One of the most influential factors affecting the priming effect is the stimulus-onset asynchrony (SOA), defined as the time between prime onset and mask onset. Typically, as the SOA increases, the priming effect increases as well (Vorberg et al., 2003).

Recently the priming effect has also been examined during movement initiation in a pointing task. Specifically, Schmidt et al. (2006) used a metacontrast masking paradigm, a common backwards masking method of rendering the prime invisible whereby the outer

contour of the prime is equal to the inner contour of the mask, to examine the influence of the mask stimulus on the processing of the prime stimulus. In this task, a green and a red prime disc were presented simultaneously in opposite quadrants of a display. After a prime-mask SOA of 17, 33, 67, or 100 ms, a green and a red annulus mask appeared in the same quadrants as the primes. In congruent trials, the same coloured prime and mask appeared in the same quadrant, whereas they appeared in opposite quadrants in incongruent trials. In addition to manipulating the prime-mask SOA, colour contrast and mask strength were manipulated in order to determine the influence of the mask on the processing of the prime stimulus. Participants were to complete a fast pointing movement to the predetermined coloured mask target. Overall, the pointing trajectory was initially guided by the direction of the prime, such that participants started moving in the incorrect direction in incongruent trials. Importantly, the spatial priming effect (i.e., the difference between the spatial pointing trajectories of incongruent and congruent trials) increased as the SOA increased and the initial spatial priming effects were time locked to prime onset and independent of the characteristics of the mask, meaning the prime and mask were processed sequentially and independently. As a result, Schmidt and colleagues (2006) proposed their rapid-chase theory outlining three criteria that, if respected, can lead one to assume that the processing of the prime stimulus occurs in an unconscious, feedforward manner based on the motor output observed in response to the prime stimulus. The rapid-chase theory integrates ideas from the feedforward sweep<sup>1</sup> (Lamme & Roelfsema, 2000) as well as from direct parameter specification (DPS; Neumann & Klotz, 1994; Neumann, 1990).

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<sup>1</sup> Although the feedforward sweep hypothesis (Lamme & Roelfsema, 2000) requires a strict feedforward processing (i.e., no recurrent processing), the rapid-chase theory does allow for some local recurrent processing to occur (T. Schmidt & Schmidt, 2009; T. Schmidt & Seydell, 2008; T. Schmidt et al., 2011).

According to the feedforward sweep hypothesis (Lamme & Roelfsema, 2000), visual information that is processed through an initial feedforward sweep is not consciously available since recurrent processing must occur for the information to reach a conscious level. In the context of the response priming paradigm, the feedforward sweep initiated by the onset of the mask stimulus interferes with the recurrent processing of the prime stimulus, leading to the inability to consciously perceive the prime. Yet, the prime can still activate its associated response without eliciting conscious awareness if its stimulus features are relevant to the task and coincide with the person's intentions as proposed by DPS (Neumann & Klotz, 1994; Neumann, 1990).

The prime is thought to be processed as a feedforward sweep if all three criteria outlined in the rapid-chase theory are met. The three criteria are the initiation criterion, the takeover criterion, and the independence criterion (T. Schmidt & Schmidt, 2009; T. Schmidt et al., 2011, 2006; Vath & Schmidt, 2007). According to the initiation criterion, the prime influences the initial trajectory of the response. However, the influence of the prime is limited since, during movement, the mask takes control of the movement such that movements are successfully completed to the goal location indicated by the mask as specified by the takeover criterion. The independence criterion ensures that the processing of the prime stimulus is unaffected by the properties of the mask as reflected in the initial kinematics (e.g., position and velocity) of the movement.

Evidence supporting the rapid-chase theory as it relates to unconscious visual processing during response initiation is provided by behavioural studies examining the priming effect when categorizing pictures (T. Schmidt & Schmidt, 2009), pointing to differently shaped targets (T. Schmidt & Schmidt, 2009), or pointing to targets cued by a



specific stimulus feature (e.g., colour or shape) (F. Schmidt & Schmidt, 2010) or by a spatial cue (T. Schmidt & Seydell, 2008). On the other hand, certain factors such as event timing, task difficulty and the presence of occluding stimuli demonstrate the limitations of the applicability of the rapid-chase theory to certain situations. When the prime-mask SOA is too short ( $<30$  ms), the prime and mask are integrated into a single stimulus (T. Schmidt et al., 2006). Furthermore, if feedback connections are required to process the prime since the task is too difficult and requires cognitive control (e.g., categorizing pictures based on their relative size), or the properties of the prime are partially occluded by overlapping stimuli then the observed motor output will not follow the criteria described in the rapid-chase theory (F. Schmidt, Weber, & Schmidt, 2014; T. Schmidt & Schmidt, 2009).

The research outlined above demonstrates that the rapid-chase theory can, under certain circumstances, be applied to unconscious processing during movement initiation of a RT or pointing task. However, it remains to be determined whether the rapid-chase theory can be applied to the processing of visual stimuli during movement execution. The application of the rapid-chase theory to ongoing movements is essential to our understanding of the limits of unconscious information processing and the role of conscious information processing in our daily lives (Kunde, Reuss, & Kiesel, 2012). It is thought that differences in processes underlying movement initiation and movement execution might exist due to mechanical ease (Christensen, Kristiansen, Rowe, & Nielsen, 2008), the involvement of the dorsal stream (Milner & Goodale, 1995, 2008), or a lowered prime activation threshold (Cressman et al., 2007). Nevertheless, no studies have examined the rapid-chase theory in the context of movement execution. To date, only a few studies investigating the influence of unconscious information processing actually presented the prime after movement onset.

These studies (Cressman et al., 2007, 2013; Fukui & Gomi, 2012) used metacontrast masking to investigate the impact of invisible primes on movement control. Participants completed a rapid aiming movement to a center target flanked by a left and a right target. The prime was presented at movement onset or after a 100 ms delay and was followed by the mask after a constant prime-mask SOA. In a proportion of the trials, participants were required to correct their movement to the left or right target in response to the mask. Overall, the results indicated that the primes did influence the control of ongoing movements since adjustments to the correct target occurred sooner in congruent compared to incongruent and neutral trials. Furthermore, participants initially made movement deviations towards the incorrect target in incongruent trials. These studies provide preliminary evidence that movement execution follows the rapid-chase criteria; specifically, the observed motor output abides by the initiation and takeover criteria. Nevertheless, the independence criterion could not be verified since the SOA was not varied.

The present experiment varied the time between prime and mask onset relative to movement onset to determine if unconscious visual stimuli are processed according to the rapid-chase theory at different time points during an ongoing movement. The importance of looking at several time points to establish the feedforward processing of the visuomotor system has been documented by previous researchers to avoid certain misconceptions about the priming effects as it changes across time (Lingnau & Vorberg, 2005; F. Schmidt, Haberkamp, & Schmidt, 2011; VanRullen & Koch, 2003). In the present study, the time between prime and mask onset was manipulated in order to investigate unconscious processing during movement execution (Experiment 1). We hypothesized based on the rapid-chase theory that the priming effect would increase as the SOA increased because the prime

would be able to influence the movement for a longer duration leading to larger overt deviations to the incorrect target in incongruent trials. Additionally, the time between movement onset and prime onset was manipulated, while keeping the prime-mask SOA constant, to determine if the influence of the primes changes depending on the time they are presented during movement (Experiment 2). We predicted that the priming effect would be unaffected given the constant SOA, but that deviations elicited by the prime and movement corrections towards the correct target would occur later as the time between movement onset and prime onset increased.

## **Methods**

### *Participants*

Twelve right-handed young adults (mean age = 21.8 years, 7 females) with normal or corrected-to-normal vision volunteered to participate in the experiment. Handedness was assessed using the modified Edinburgh handedness inventory (Oldfield, 1971; mean score =  $71.9 \pm 18.7$ ). The study was approved by the University of Ottawa Health Sciences and Science Research Ethics Board. Prior to data collection, participants provided written informed consent.

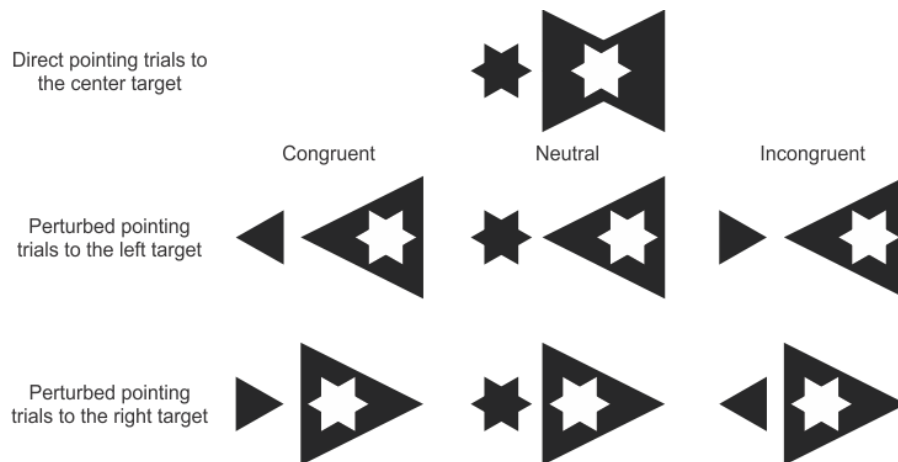
### *Experimental Set-up*

Participants were seated approximately 10 cm from the edge of the table in a dimly lit room. Participants performed the task with their right hand. An infrared-emitting diode, positioned on the tip of the participants' right index finger, was monitored using an OPTOTRAK (Northern Digital, Waterloo, Ontario) motion analysis system, with a spatial resolution of 0.01 mm. In each trial (outlined below) data were collected at a sampling frequency of 500 Hz for a duration of 3 s. The stimuli were projected from a Samsung 245B

LCD monitor (refresh rate of 60 Hz and a response time of 5 ms), onto a reflective surface that was placed 28 cm below the monitor so that the stimuli appeared to lie in the same plane as the occluded right hand.

### *Stimuli*

Stimuli were presented using C/C++ software, within which a custom written timer was created to ensure the proper timing of all events. All stimuli were white on a black background. The 17 ms prime stimulus consisted of a left-pointing arrow, a right-pointing arrow, or a neutral prime. The dimensions of the arrow primes were 4 x 9 mm. The neutral star shaped prime was constructed by superimposing the left and right arrow primes. The mask stimulus consisted of a left-pointing arrow, a right-pointing arrow, or a neutral mask. The arrow masks were similar in shape to the arrow primes but were larger in size (23 x 28 mm) (see Figure 1). The center of each mask had a cut-out of the neutral shape such that the outer contour of the neutral prime equalled the inner contour of the masks.



*Figure 1.* Prime-mask stimuli presented in the direct pointing trials (top row) and in the perturbed pointing trials (left mask: middle row; right mask: bottom row), separated by the different prime-mask combinations (congruent, neutral, and incongruent).

*Procedure*

Participants completed two mask pointing tasks and a prime identification task. The two mask pointing tasks were completed on separate days. The mask pointing tasks differed with respect to the timing of the stimulus sequence. In one task, the time between prime and mask onset was manipulated by presenting the prime at movement onset and varying the prime-mask SOA between 33, 50, and 67 ms (Experiment 1). The start of the movement began when the finger moved a resultant distance of 10 mm from its initial location on the home position, which was determined by monitoring the finger position data online using a windows socket (Winsock). In the other task, the time between prime and mask onset was constant at 50 ms, but prime presentation followed movement onset by a time of 17, 33, or 50 ms (Experiment 2). The two tasks were completed in different sessions, each lasting between 1.5 to 2 hours. The mask pointing tasks were counterbalanced between participants.

In both mask pointing tasks, participants placed their right index finger on the home position indicated by a white circle (1 cm in diameter) that was approximately 20 cm in front of their body and aligned with their body midline. The three targets (33 x 33 mm) consisted of a white square outline. The distance from the center of the circular home position to the center of the middle target was 27 cm and the distance from the center of the middle target to the center of the left and right targets was 7 cm (see Figure 2). Participants fixated on the middle white square target displayed in the center of the screen. Participants could initiate their response to the middle target at any time once the outline of the target boxes became bold (go-signal), so long as their movement was complete within 3 seconds following the go-signal. Participants were told to initiate their response by lifting their finger and moving it

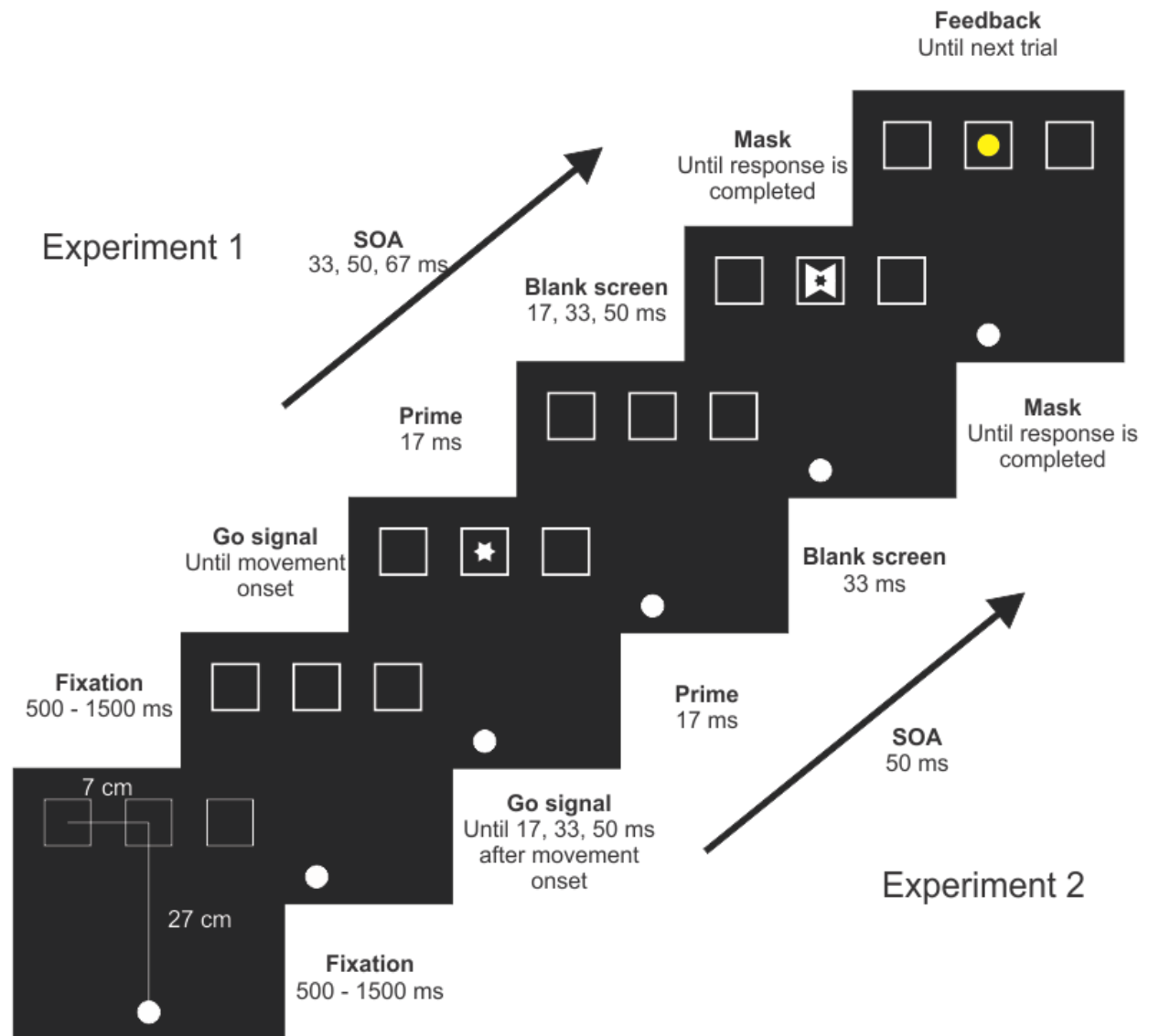
towards the middle target. The task was not a reaction time task, but participants were given a movement time goal of 400-600 ms.

After movement onset, a prime was presented in the middle target. The prime was either a left-pointing arrow, a right-pointing arrow, or a neutral star shape. A blank screen followed the prime which in turn was followed by the mask. The mask indicated the target location and remained on the screen, in the middle target box, until the response was complete.

In Experiment 1, the prime was presented in the middle target at movement onset, defined as the time when the finger moved 10 mm from the home position. In this case, the prime-mask SOA varied between 33, 50, and 67 ms. In the other task, the prime-mask SOA was constant at 50 ms but the onset of the prime relative to movement onset varied between 17, 33, and 50 ms (see Figure 2).

In 2/3 of the testing trials (direct pointing trials), a neutral prime was followed by a neutral mask and, in this case, participants were instructed to complete their movement initiated to the middle target box (see Table 1). After each direct pointing trial, participants received verbal feedback on their MT. MT was defined online as the time from when the finger moved 10 mm from its initial position on the home position until velocity fell below 0.01 m/s (provided that it remained below 0.01 m/s for 500 ms). Terminal feedback regarding final position was provided on all direct pointing trials by a yellow circle (1 cm in diameter) appearing directly above the location where the movement was completed, regardless of where the finger landed (i.e., inside or outside the target). In the remaining 1/3 of the testing trials (perturbed trials), the left- or right-pointing arrow mask was presented requiring participants to modify their initial movement and move to the left or right target

box, respectively. In these trials, the mask was preceded by the neutral, left- or right-pointing arrow prime. The perturbed trials were divided equally among the neutral, congruent, and incongruent prime-mask conditions. No feedback with regards to MT was provided on these trials, but participants did receive terminal feedback regarding their endpoint position.



*Figure 2.* The time course of stimulus presentation for the mask pointing task in Experiment 1 (on the left) and Experiment 2 (on the right). The trial sequence depicts a direct pointing trial requiring a movement to the middle target since both prime and mask were neutral. SOA: stimulus onset asynchrony

Participants began each mask pointing session with a practice block of 20 trials to the middle target to get accustomed to the task and MT goal. In the practice trials, a neutral prime and mask were presented with a prime-mask SOA of 50 ms. Participants then completed 540 randomized mask pointing trials with the restriction that no more than 3 perturbed trials were presented in a row and that at the beginning of every 108 trials (which coincided with self-terminated breaks) the first 5 trials were direct pointing trials. A breakdown of the number of trials completed in each mask pointing task separated by prime-mask congruency is presented in Table 1. Overall, there were a total of 18 different perturbed trial combinations per experiment since there were 3 prime shapes, 2 directional mask shapes, and 3 varying times for stimuli presentation (Experiment 1: prime-mask onset and Experiment 2: movement-prime onset).

Table 1

*The breakdown of the 540 trials for each of the mask pointing tasks based on the number of trials for each prime-mask combination. The table is further divided by the time between prime offset and mask onset for Experiment 1 and the time between movement onset and prime onset for Experiment 2. The neutral mask appeared in 2/3 of the trials and each prime stimulus occurred with equal probability in trials with a directional mask.*

|                                    |             | <b>Experiment 1:</b> Time between prime offset and mask onset<br><b>Experiment 2:</b> Time between movement onset and prime onset |       |       | Total |
|------------------------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------|-------|-------|-------|
| Mask shape                         | Prime shape | 17 ms                                                                                                                             | 33 ms | 50 ms |       |
| Neutral                            | Neutral     | 120                                                                                                                               | 120   | 120   | 360   |
| Directional<br>(left and<br>right) | Congruent   | 20                                                                                                                                | 20    | 20    | 60    |
|                                    | Incongruent | 20                                                                                                                                | 20    | 20    | 60    |
|                                    | Neutral     | 20                                                                                                                                | 20    | 20    | 60    |
| Total                              |             | 180                                                                                                                               | 180   | 180   | 540   |



Following the second session of the mask pointing task, participants were made aware of the prime stimulus and completed a prime identification task to assess their conscious awareness of the primes. Presentation of the prime and mask in the prime identification task differed slightly from that of the mask pointing task. First, participants did not execute a movement, but were instructed to keep their right index finger on the home position during the entire task. Furthermore, since participants did not execute a movement, the prime appeared 1500 ms after the targets turned bold and the mask remained on the screen for 500 ms. Similar to the mask pointing task, prime shape and prime-mask SOA were randomized. In contrast to the mask pointing task, the mask shapes were not randomized and one block of trials contained neutral masks while the other block contained directional masks (i.e., randomized between left and right-pointing arrow masks), as the shape of the mask has been shown to bias participants' responses (Albrecht & Mattler, 2012; Vermeiren & Cleeremans, 2012). Participants were told that each prime was presented with the same probability and that they had to try and identify the shape of the prime. If they were unsure, they were asked to provide their best guess. To avoid any indirect priming effects (see Vorberg et al., 2003), participants verbally reported their answer 500 ms after mask onset, which was denoted by the disappearance of the mask. In addition to the objective measures, subjective measures were included to capture participants' perception of their visual experience. Following the 3-alternative forced choice task, participants rated their perceptual awareness using a perceptual awareness scale with values ranging from 1 to 5. The scale was adopted from Christensen et al. (2008), where the values 1 to 5 were associated with (1) "no perception of a stimulus", (2) "possible vague perception of a stimulus without the ability to identify it", (3) "definite perception of a stimulus without the ability to identify it", (4)

“definite perception of a stimulus with the possible ability to identify it”, and (5) “definite perception of a stimulus with a definite ability to identify it”. Participants’ responses were manually entered by the experimenter. There was no time limit for identifying the prime or providing a perceptual awareness rating since accuracy was the main objective of the task. In addition, no feedback was provided regarding the shape of the prime stimulus.

Before each prime identification block, participants viewed three trials in which each prime was presented for 167 ms with a prime-mask SOA of 334 ms so that the participants could clearly see each prime once before the start of the testing session. This also allowed the participants to familiarize themselves with the shape of the primes and the type of responses required. Participants completed one prime identification block with neutral masks and one with directional masks. Each block contained 10 trials for each prime shape and prime-mask SOA combination resulting in 90 trials per block for a total of 180 trials. The order of the blocks was counterbalanced between participants.

### *Data Analyses*

For the perceptual data, the proportion of correct responses in the objective task were submitted to an arcsin-square root transformation and a repeated measures analysis of variance (RM ANOVA) was used to compare the data across conditions of block (neutral or directional mask), SOA (33, 50, 67 ms), and prime direction (left, right or neutral). Additionally, the proportion of correct responses was compared to chance levels (33%) using a t-test. For the subjective task, the frequency of each response on the perceptual awareness scale was calculated as a percentage and reported as a descriptive measure.

In the mask pointing task, each pointing trajectory (x (lateral) and y (forward) coordinates) was plotted using Matlab software (Mathworks Inc, version 8.4.0), along with

the corresponding velocity and acceleration profiles. The start position corresponded to the time when the finger first moved 10 mm from the home position and end position was manually selected and corresponded to the time at which velocity fell below 0.01 m/s without rising above 0.01 m/s for another 50 ms. To determine the time at which participants made corrections in the perturbed trials, each perturbed pointing trajectory was compared to the mean spatial trajectory of all direct pointing trials. Regardless of SOA, a similar path length and endpoint location was obtained for all direct pointing trials as confirmed by two 3 SOA repeated measures (RM) ANOVAs (see Results); therefore, a 2 dimensional average spatial path was computed from all direct pointing trials within the experiment (Experiment 1 or Experiment 2) for each participant. The x coordinate was computed by deriving the mean lateral spatial position at every 2 mm of forward movement progression. If a trial did not have an x position value at the exact y location, the x coordinate was obtained by linear interpolation from the closest data points. In addition, the standard deviation of the mean position in the x direction was calculated across trials. The time of correction was determined by comparing each perturbed pointing trajectory to the calculated mean spatial trajectory of the direct pointing trials with its 2 standard deviation (SD) bandwidth (see Cressman, Franks, Enns, & Chua, 2006). Specifically, the time of correction to the correct target (i.e., in response to the visible mask in neutral or incongruent trials) was defined as the time at which displacement in the horizontal axis of the movement reached a minimum or maximum value and showed a reversal to the appropriate eccentric target. In perturbed trials, errors were defined as trials in which participants landed within the 2 SD bandwidth of the average endpoint position of the direct pointing trials or landed on the opposite target; thus, they

failed to reach the proper target. Path length was calculated by adding each increment of distance travelled between two subsequent time points over the course of the trajectory.

Additional analyses involved computing an average spatial trajectory for each condition of perturbed trials in the horizontal direction which also allowed us to examine the priming effect. This was determined by averaging each individual's average x position across time for a specific prime-mask combination and SOA (Experiment 1) or Delay (Experiment 2). Given that the average time of correction was greater than 250 ms, we looked to establish the maximum horizontal position achieved after 250 ms, which was defined as the maximal or minimal horizontal position achieved before average spatial trajectories were corrected to the appropriate left or right eccentric target, respectively. The time associated with this maximum position was also recorded. The time when participants started to move in the correct direction was defined as the point in time when the lateral position exceeded 2 SD of the group average lateral position calculated over the first 250 ms of the movement (see Figure 3).

Unless specified otherwise, a 2 Mask (Left, Right) x 3 Congruency (Congruent, Neutral, Incongruent) x 3 SOA (33, 50, 67 ms) within-subjects RM ANOVA was used to analyse the data in Experiment 1 and a similar RM ANOVA was used in Experiment 2 where the factor SOA was replaced by the factor Delay (17, 33, 50 ms). If the assumption of sphericity was violated then the Greenhouse-Geisser correction factor was used and post-hoc tests were conducted using the Bonferroni correction. The data are reported as mean values with their associated standard deviation.

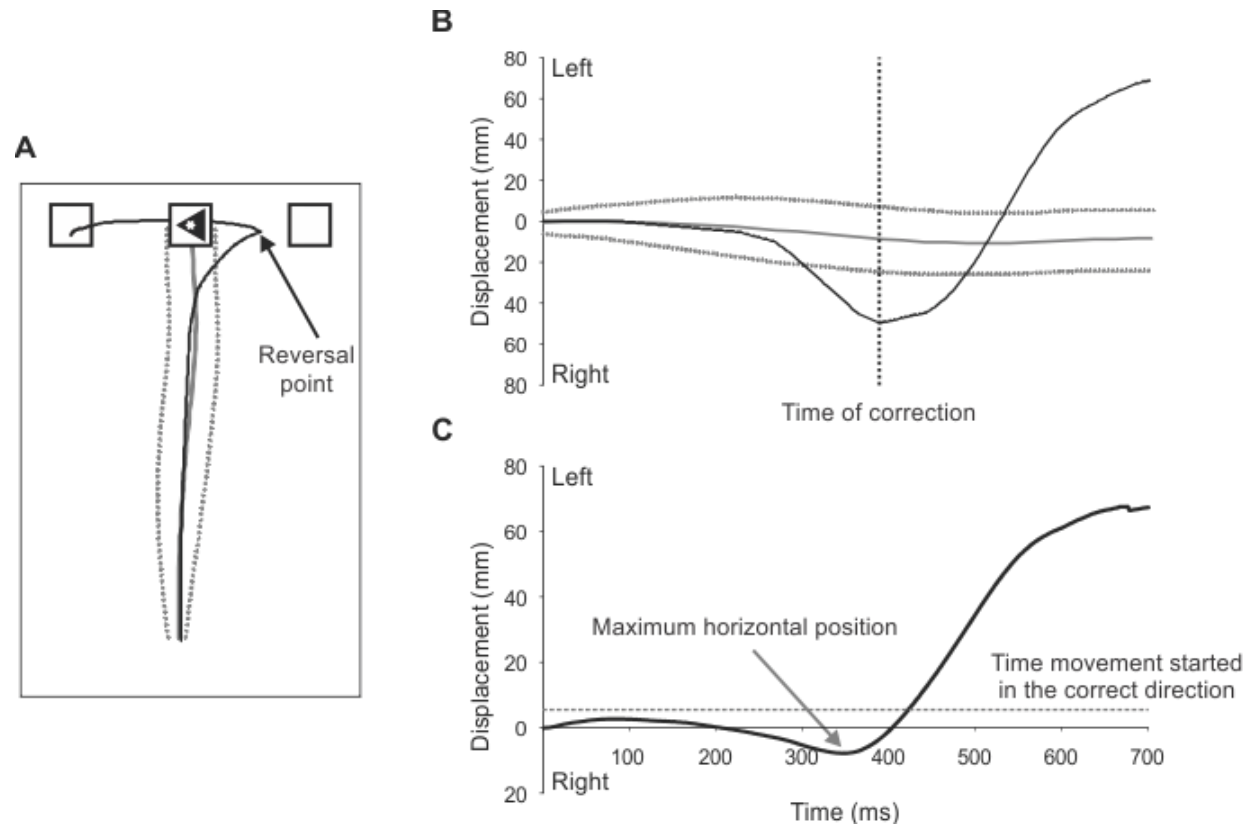


Figure 3. **A)** A single pointing trajectory in an incongruent trial where a right prime arrow preceded a left mask arrow (black solid line). This single trial was compared to the participant's average spatial trajectory in direct pointing trials (solid gray line) with its 2 standard deviation (SD) bandwidth (dotted gray line). Notice that the trajectory was first modified in the direction of the prime arrow but was then corrected to the target indicated by the mask. The solid black arrow indicates the reversal point where the movement started moving in the correct direction defined as the time of correction. **B)** Displacement in the lateral direction as a function of time for the corresponding pointing trajectory depicted in **A)**. Once again the average spatial trajectory in direct pointing trials with its 2 SD bandwidth is shown. The dotted black line represents the point in time where the reversal point occurred. **C)** An individual's average lateral position over time for a single prime-mask combination and stimulus onset asynchrony (SOA; Experiment 1) or Delay (Experiment 2). The gray arrow indicates the maximum horizontal position while the gray dotted line represents the time participants moved in the correct direction.

## Results

### Prime Identification

Due to errors in data collection, 3 objective response trials (0.14%) and 4 subjective response trials (0.19%) were not recorded.

Participants' objective awareness in the prime identification task was first analyzed by comparing their total percent of correct responses ( $44.5\% \pm 5.6$  SD) across both blocks to chance levels (33%) using a t-test, which resulted in a significant difference,  $t(11) = 9.519$ ,  $p < 0.001$ . A 2 Block x 3 SOA RM ANOVA was then performed and revealed no significant main effects for Block,  $F(1,11) = 2.855$ ,  $p = 0.119$ , or for SOA,  $F(2,22) = 1.276$ ,  $p = 0.299$ .

Since there was no significant main effect for SOA or Block, we focussed the remainder of our analysis on the block with the directional masks because these trials were similar to those in which participants had to make a correction to the left or right target in the mask pointing task. A 3 Congruency RM ANOVA revealed that there was a main effect for Congruency,  $F(2, 22) = 3.457$ ,  $p = 0.049$ , but post-hoc tests did not reveal any significant differences between the congruency conditions. However, the neutral prime condition was the only condition where performance was significantly above chance,  $t(11) = 3.787$ ,  $p = 0.003$ . Consequently, participants were not aware of the directional primes above chance levels in perturbed trials. This was further confirmed by participants' subjective awareness responses (see Table 2), which revealed that participants reported "no perception of a stimulus" on the majority of trials at all SOAs. As a result, any differences in movement trajectory seen between congruent and incongruent trials cannot be attributed to perception of the prime stimulus.

Table 2

The percentage (%) of correct responses and frequency (%) of perceptual awareness responses with their associated standard deviations for the prime identification task separated by block and prime-mask stimulus onset asynchrony (SOA). The percent correct was further divided by prime shape (neutral and directional). Note that 1 indicated “no perception of a stimulus” and 5 indicated “definite perception of a stimulus with a definite ability to identify it”.

| Block                                           |                 | Neutral Mask   |                |                |                | Directional Mask |                |                |                |
|-------------------------------------------------|-----------------|----------------|----------------|----------------|----------------|------------------|----------------|----------------|----------------|
| SOA                                             | Prime direction | 33 ms          | 50 ms          | 67 ms          | Total          | 33 ms            | 50 ms          | 67 ms          | Total          |
| Percent correct (%)                             | Neutral         | 60.8<br>(19.3) | 57.5<br>(19.1) | 56.7<br>(18.3) | 58.3<br>(18.4) | 49.6<br>(22.8)   | 55.8<br>(21.5) | 64.2<br>(23.5) | 56.5<br>(22.8) |
|                                                 | Directional     | 36.0<br>(8.7)  | 40.4<br>(12.1) | 43.8<br>(11.5) | 40.0<br>(11.1) | 35.8<br>(14.6)   | 35.8<br>(13.8) | 35.9<br>(13.7) | 35.9<br>(13.6) |
|                                                 | Total           | 48.4<br>(19.4) | 49.0<br>(17.9) | 50.2<br>(16.3) | 49.2<br>(17.7) | 42.7<br>(20.0)   | 45.8<br>(20.4) | 50.0<br>(23.7) | 46.2<br>(21.4) |
| Response                                        |                 |                |                |                |                |                  |                |                |                |
| Frequency of perceptual awareness responses (%) | 1               | 60.7<br>(18.6) | 60.6<br>(15.6) | 59.4<br>(17.9) | 60.2<br>(16.9) | 57.4<br>(26.4)   | 60.0<br>(20.1) | 61.2<br>(16.5) | 59.6<br>(20.8) |
|                                                 | 2               | 17.3<br>(13.8) | 14.2<br>(16.2) | 13.9<br>(14.3) | 15.1<br>(14.4) | 20.3<br>(18.5)   | 20.3<br>(22.1) | 15.6<br>(16.0) | 18.7<br>(18.6) |
|                                                 | 3               | 6.7<br>(6.7)   | 5.3<br>(5.2)   | 7.2<br>(5.3)   | 6.4<br>(5.7)   | 12.8<br>(7.4)    | 9.4<br>(7.2)   | 10.3<br>(7.4)  | 10.9<br>(7.3)  |
|                                                 | 4               | 6.7<br>(5.3)   | 10.0<br>(7.1)  | 10.6<br>(6.5)  | 9.1<br>(6.4)   | 7.2<br>(7.6)     | 6.4<br>(5.8)   | 7.8<br>(6.9)   | 7.1<br>(6.6)   |
|                                                 | 5               | 8.6<br>(11.5)  | 10.0<br>(10.2) | 8.9<br>(9.0)   | 9.2<br>(10.0)  | 2.2<br>(3.3)     | 3.9<br>(4.0)   | 5.0<br>(5.6)   | 3.7<br>(4.4)   |

## Experiment 1

### Direct Pointing Trials

A total of 2.66% of the direct pointing trials, trials in which a neutral prime and mask were presented, were lost because the marker was not visible or the participant did not finish

their movement within 3 s after the go signal. On the remaining trials, participants completed their movements within the movement time goal (average MT = 505.8 ms  $\pm$  23.3 SD) and landed within the center target. Average performance measures of these remaining trials were submitted to a 3 SOA RM ANOVA. Analyses revealed that there were no significant differences in MT, path length or endpoint position between the different SOAs (MT:  $F(2,22) = 3.310, p = 0.055$ ; Path length:  $F(2,22) = 0.450, p = 0.643$ ; x endpoint position:  $F(2,22) = 1.141, p = 0.338$ ; y endpoint position:  $F(2,22) = 2.154, p = 0.140$ ). Furthermore, endpoint variable error did not differ between the different SOA conditions as there was no significant main effect for SOA in the x direction,  $F(2,22) = 0.845, p = 0.443$ , or the y direction,  $F(2,22) = 0.072, p = 0.931$ . Consequently, SOA did not influence movement time, pointing trajectories or final position when the prime and mask were neutral.

#### Perturbed pointing trials

A total of 4.91% of the trials were lost because the marker was not visible or participants did not complete the movement within 3 s after the go signal. An additional 7 trials (0.34%) were excluded from analysis because participants went straight to the correct target location without initiating their movements to the center target.

To extend the rapid-chase theory to movement execution it must be shown that all three criteria were followed. By examining the number of successful corrections to the appropriate target it can be determined whether the mask was capable of exerting its influence before the movement was completed as outlined by the takeover criterion. In fact, 88.2%  $\pm$  12.7 SD of the perturbed trials were successful such that participants corrected their movement to the appropriate target (see Table 3 for average error results). Thus, the masks were capable of taking over the movement. On trials that were not corrected, participants



landed on the center target. The number of these error trials were modulated by SOA,  $F(2,22) = 5.945$ ,  $p = 0.009$ , and Congruency,  $F(2,22) = 4.419$ ,  $p = 0.024$ , such that more errors occurred with a 67 ms SOA compared to a 33 ms SOA,  $p = 0.027$ , and more errors were committed in the neutral prime trials compared to incongruent trials,  $p = 0.026$ .

Having established that the masks took over control of the movement on the majority of trials, we next looked to determine the prime's influence on performance. The subsequent analyses were performed only on successfully completed perturbed trials (i.e., trials completed to the correct left and right targets). Importantly with these trials, the prime-mask SOA did not affect average final endpoint position achieved or the variability around this position when pointing to the left and right targets ( $p > 0.05$ ). To demonstrate that the prime influenced the trajectory of the movement as stated by the initiation criterion, we must show that the prime influenced kinematic variables such as time, position, and velocity by showing a difference between congruency conditions.

In support of the initiation criterion, MT analyses revealed main effects for Mask,  $F(1, 11) = 38.981$ ,  $p < 0.001$ , Congruency,  $F(2,22) = 17.701$ ,  $p < 0.001$ , and SOA,  $F(2,22) = 78.444$ ,  $p < 0.001$ . Overall, MT was significantly longer when pointing to the left target compared to the right target. As expected, MT in congruent trials was significantly shorter in the congruent than in the incongruent and neutral conditions,  $p < 0.001$  and  $p = 0.018$ , respectively. No significant differences were observed between the incongruent and neutral trials,  $p = 0.212$ . The 67 ms SOA condition was significantly slower than the 33 ms SOA and the 50 ms SOA condition, both  $p < 0.001$ . Although average MT was faster with a 33 ms SOA compared to a 50 ms SOA, the result did not reach significance,  $p = 0.060$ , but a

significant linear trend was present,  $F(1,11) = 177.650$ ,  $p < 0.001$ , suggesting movement time increased with an increase in SOA.

Table 3

*Average errors (%), movement times (ms), time of corrections (ms) and velocity at correction (m/s) in Experiment 1 separated by SOA (33 ms, 50 ms, and 67 ms) and Congruency (Congruent (C), Neutral (N), and Incongruent (I)) with the associated standard deviation. The results are collapsed across the directional masks (Both) when no significant differences were observed between the left and right-pointing arrow masks.*

| SOA                             |       | 33 ms           |                 |                 | 50 ms           |                 |                 | 67 ms           |                 |                 |
|---------------------------------|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Congruency                      | Mask  | C               | N               | I               | C               | N               | I               | C               | N               | I               |
| Errors (%)                      | Both  | 8.4<br>(9.6)    | 11.8<br>(16.6)  | 6.5<br>(10.3)   | 11.8<br>(15.8)  | 17.3<br>(20.6)  | 10.0<br>(13.7)  | 12.1<br>(15.5)  | 16.4<br>(19.1)  | 14.4<br>(18.5)  |
| Movement time<br>(ms)           | Left  | 640.8<br>(51.7) | 649.7<br>(47.9) | 665.2<br>(52.6) | 643.4<br>(51.8) | 657.7<br>(50.0) | 676.2<br>(58.0) | 674.6<br>(54.7) | 697.6<br>(69.1) | 699.8<br>(58.0) |
|                                 | Right | 588.1<br>(62.3) | 607.7<br>(59.4) | 612.4<br>(61.5) | 599.8<br>(56.2) | 620.0<br>(65.4) | 622.0<br>(62.7) | 611.7<br>(47.8) | 632.8<br>(51.8) | 648.5<br>(59.0) |
|                                 | Both  | 614.4<br>(62.1) | 628.7<br>(57.0) | 638.8<br>(62.1) | 621.6<br>(57.4) | 638.8<br>(60.1) | 649.1<br>(65.2) | 643.2<br>(59.6) | 665.2<br>(68.3) | 674.1<br>(62.9) |
| Time of correction<br>(ms)      | Both  | 324.3<br>(24.1) | 337.6<br>(22.8) | 348.4<br>(32.5) | 335.3<br>(28.3) | 348.4<br>(28.2) | 353.3<br>(24.6) | 349.8<br>(33.8) | 361.4<br>(24.9) | 376.2<br>(29.8) |
| Velocity at<br>correction (m/s) | Both  | 0.362<br>(0.11) | 0.313<br>(0.12) | 0.262<br>(0.11) | 0.319<br>(0.12) | 0.284<br>(0.11) | 0.264<br>(0.11) | 0.273<br>(0.11) | 0.217<br>(0.08) | 0.202<br>(0.08) |

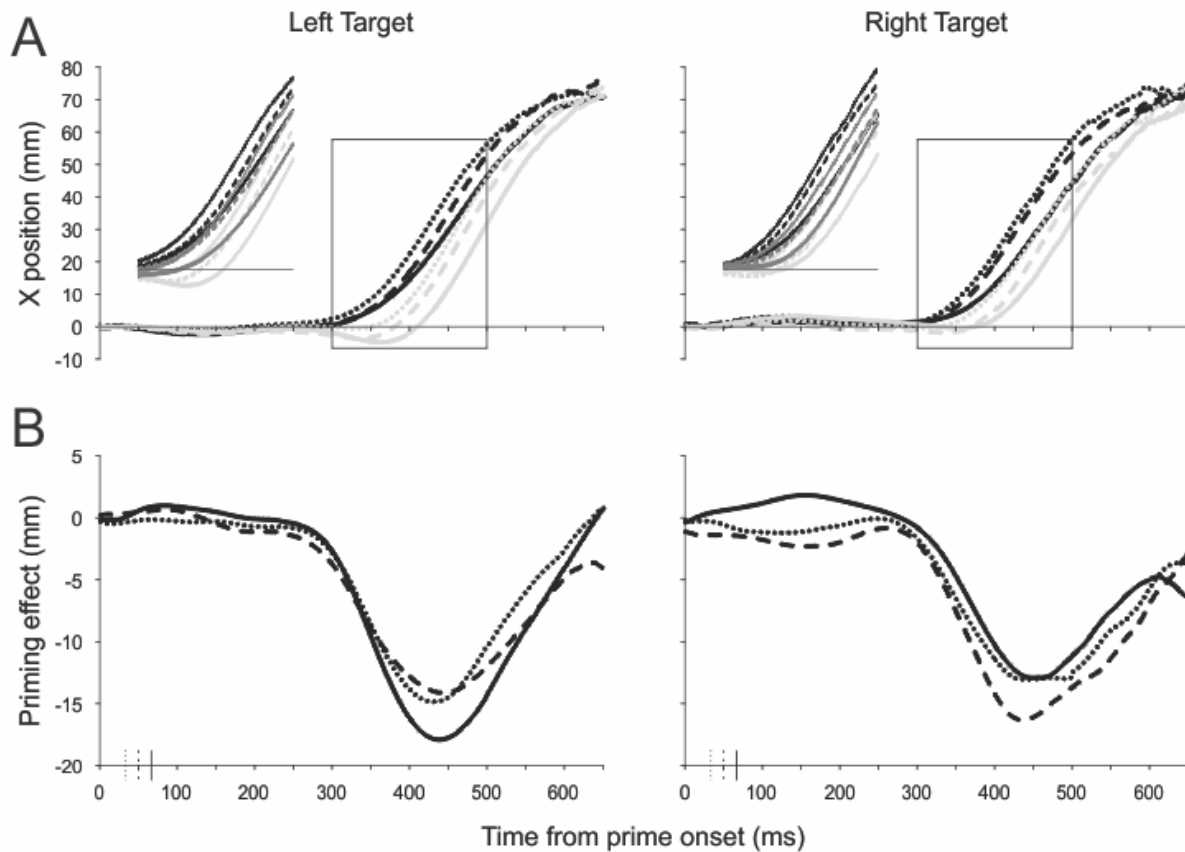
In addition to the MT data, the time, resultant velocity, and position at the time of the correction toward the correct target, indicated by the mask, provides further support in favour of the initiation criterion suggesting that the prime influenced the pointing trajectory.

Specifically, the analysis of the time of correction resulted in a significant main effect for Congruency,  $F(2,22) = 26.368$ ,  $p < 0.001$ , revealing that corrections occurred sooner in the congruent condition compared to the incongruent and neutral conditions,  $p \leq 0.011$ , and corrections occurred sooner in the neutral condition compared to the incongruent condition,  $p = 0.035$ . Furthermore, there was a main effect for SOA,  $F(2,22) = 62.574$ ,  $p < 0.001$ , because

corrections occurred later as the SOA increased. The 67 ms SOA condition was significantly different from the 33 ms and the 50 ms conditions,  $p < 0.001$ , and the difference between the 33 ms and 50 ms conditions was also significant,  $p = 0.044$ .

When examining participants resultant velocity at the time of these corrections, there was a significant main effect for Congruency,  $F(2,22) = 30.309$ ,  $p < 0.001$ , such that the velocity in the congruent condition was significantly faster than in the incongruent and the neutral conditions, both  $p = 0.002$ . The difference between the neutral and incongruent trials approached significance,  $p = 0.056$ . A significant main effect was also found for SOA,  $F(2,22) = 32.011$ ,  $p < 0.001$ , as the velocity at the 67 ms SOA was significantly slower than the velocity at the 33 ms and the 50 ms SOA, both  $p < 0.001$ . There was no significant difference between the 33 ms and 50 ms SOA,  $p = 0.222$ ; however, the linear trend was significant,  $F(1,11) = 67.815$ ,  $p < 0.001$ , indicating that the velocity decreased as the SOA increased.

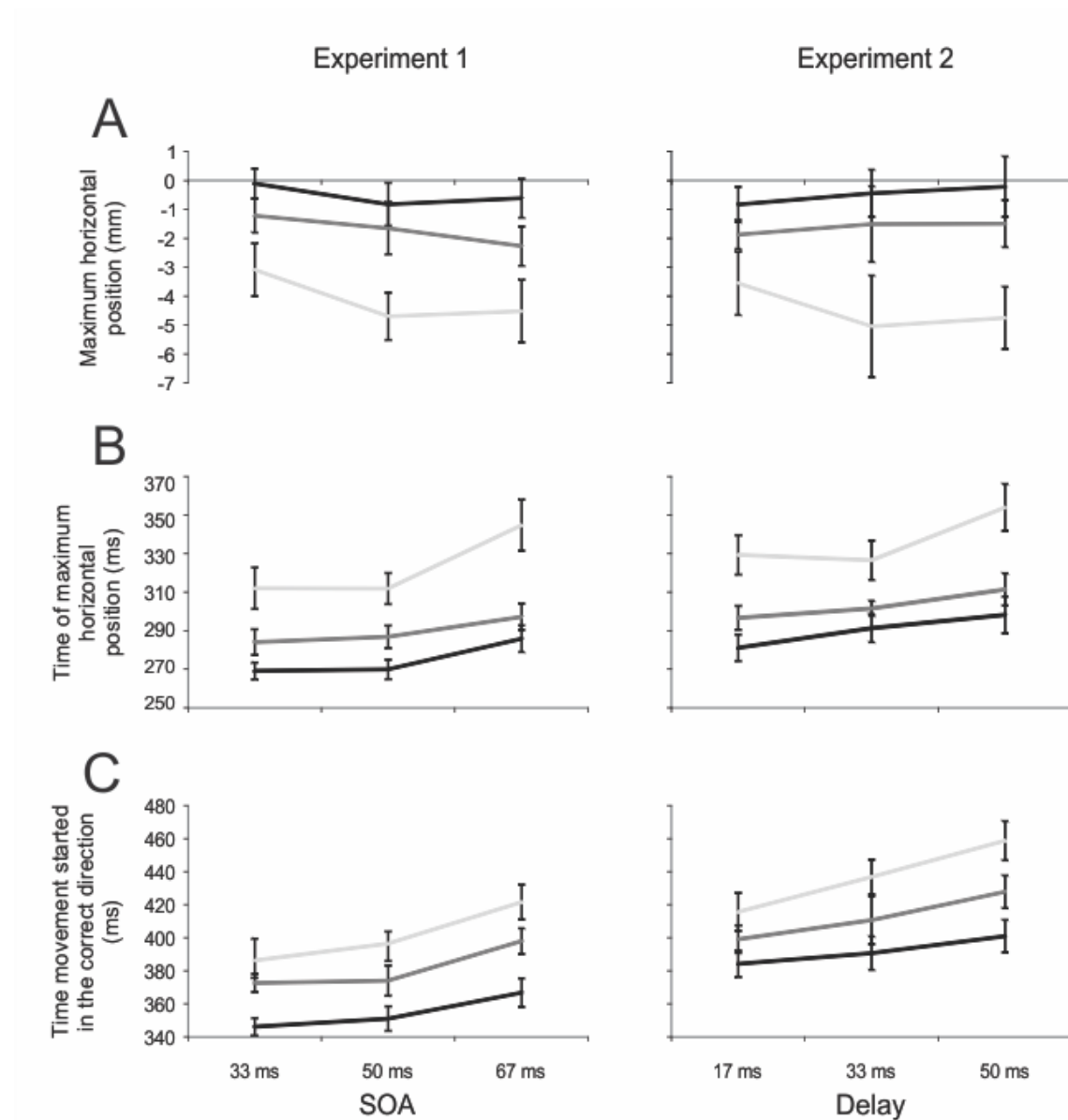
Participants' horizontal position at the time of these corrections to the correct target, showed a significant Mask x Congruency interaction,  $F(2,22) = 30.043$ ,  $p < 0.001$ . For both masks, participants were significantly closer to the correct target in the neutral and congruent conditions compared to the incongruent condition. This resulted in a significant interaction with the factor Mask because corrections occurred in opposite directions based on the direction of the mask stimulus. This deviation towards the incorrect target in incongruent trials is highlighted in the average spatial trajectories (see Figure 4A), where participants clearly started moving in the direction indicated by the prime before making a second correction towards the correct target.



**Figure 4. A)** The average spatial trajectory and **B)** the spatial priming effect (incongruent – congruent) when pointing to the left and right targets in Experiment 1 as a function of prime onset (i.e., movement onset). The various lines represent the different congruency (congruent: black; neutral: dark gray; incongruent: light gray) and prime-mask SOA conditions (33 ms: dotted; 50 ms: dashed; 67 ms: solid). The vertical lines on the x-axis indicate the time of mask onset. For clarity the neutral prime condition is excluded in the top figures but is presented from 300-500 ms in the inset. Positive values indicate movement in the correct direction while negative values indicate movement in the incorrect direction.

Overall, the current analysis of the kinematic variables supports both the initiation and takeover criterion of the rapid-chase theory. The prime initially influenced the direction of the movement supporting the initiation criterion. On most trials, participants were able to finish their movement at the correct target location providing evidence for the takeover criterion. Participants corrected and completed their movement earlier in the congruent condition compared to the neutral and incongruent conditions, most likely, due to the

increased velocity at the time of correction and the lack of deviation in the incorrect direction. We next looked to determine whether or not the data fits the prediction of the independence criterion. To do this, we established the influence of SOA on the lateral spatial priming functions. Specifically, the spatial priming effect should initially be the same for all SOA conditions, such that all priming functions follow the same average time course, as they are initially controlled by the prime. Once the mask starts to exert its influence on the prime the different priming functions would be expected to deviate one at a time from the remaining invariant functions. Specifically, the priming functions would start to individually deviate from the common time course in a predictable manner based on the prime-mask SOA with the short SOAs deviating before the long SOAs. Moreover, the rapid-chase theory predicts that the maximum horizontal position achieved, the corresponding time at which this position occurred and the time when participants started moving towards the correct target should be similar across SOAs in congruent trials. In contrast, these variables should show an increase in incongruent trials as the SOA increases because the prime would control the movement for a longer duration resulting in larger deviations in the incorrect direction, which is reflected by a larger priming effect. With respect to the neutral condition, similar maximum distance values should be seen across SOAs since participants would be travelling straight ahead to the center target. However, the time when participants start moving in the correct direction should also increase in the neutral condition.



**Figure 5. A)** The maximum horizontal position **B)** the time of maximum horizontal position and **C)** the time when the movement started in the correct direction relative to movement onset collapsed across the left and right masks as a function of the different stimulus onset asynchrony (SOA) (Experiment 1: left side) and Delay (Experiment 2: right side) conditions. Congruent: black lines; Neutral: dark gray lines; Incongruent: light gray lines. Error bars represent the standard error of the mean.

These predictions are not supported by the analyses of additional kinematic variables derived from participants' average lateral position over time as shown in Figure 5A or

observed in the lateral spatial priming functions shown in Figure 4B. Specifically, both the maximum horizontal position,  $F(4,44) = 0.286$ ,  $p = 0.792$ , and the time at which this maximum distance was attained,  $F(4,44) = 0.927$ ,  $p = 0.457$ , failed to show a significant Congruency x SOA interaction as predicted by the independence criteria (see Figure 5A and B). In the incongruent condition, the maximum horizontal position did not increase between the 50 ms and 67 ms SOA nor did the time at which this value occur increase between the 33 ms and 50 ms condition. There were no significant main effects for Mask so the results are collapsed across directional masks.

As outlined above, the time when participants started moving in the correct direction should be achieved at the same time in all congruent trials but should be later with increasing SOA in both neutral and incongruent trials. As seen in Figure 5C this is not the case, as it appears that the time when participants started moving in the correct direction slightly increased with SOA for all prime-mask congruency conditions. This was confirmed by finding no significant Congruency x SOA interaction,  $F(4,44) = 0.394$ ,  $p = 0.714$ ; thus providing additional support that the observed motor output does not respect the independence criterion.

The independence criterion is further refuted by observing the priming effect functions found in Figure 4B. When pointing to both the left and right targets, it can be seen that the priming effect functions do not follow the rapid-chase theory. Even though the three functions share an initial similar time course, the point at which they deviate and the maximum priming amplitude achieved is incompatible with the prediction of the rapid-chase theory. For the left mask, the spatial priming effect for the 50 ms SOA appears to deviate from the average time course before the 33 ms SOA which in turn deviated before the 67 ms

condition. Furthermore, the 33 ms and 50 ms conditions resulted in similar amplitudes suggesting that the prime influenced the pointing trajectory to the same extent in the 33 and 50 ms conditions. For the right target, the spatial priming effect in the 67 ms condition is similar to that of the 33 ms condition as they both followed the same time course and achieved similar amplitudes while the 50 ms condition followed a different time course and had the greatest priming amplitude. Consequently, the data does not support the independence criterion of the rapid-chase theory since the priming functions do not deviate from the average time course according to the relative timing of the stimuli.

## Experiment 2

### Direct Pointing Trials

A total of 3.33% of the direct pointing trials were not recorded because the marker was not visible or the participant did not finish their movement within the 3 s allotted time. In the remaining trials, participants completed their movements within the goal MT (average MT = 511.1 ms  $\pm$  28.7 SD) to the center target. Performance measures for these trials were analyzed using a 3 Delay RM ANOVA. The MT analysis revealed a main effect for Delay,  $F(2,22) = 12.965$ ,  $p < 0.001$ . Post-hoc tests showed that when the prime was presented 17 ms after movement onset, MT was significantly faster (501.4 ms  $\pm$  26.9 SD) compared to when the prime was presented 33 ms (512.2 ms  $\pm$  32.1 SD,  $p = 0.017$ ) or 50 ms (519.8 ms  $\pm$  29.7 SD,  $p = 0.004$ ) after movement onset. The difference between 33 ms and 50 ms was not significant ( $p = 0.135$ ). Similar to Experiment 1, there were no significant differences in the distance travelled in either delay conditions,  $F(2,22) = 1.950$ ,  $p = 0.166$ , as determined by the path length. Additionally, no significant differences were observed with respect to endpoint position in the x,  $F(2,22) = 0.648$ ,  $p = 0.533$ , and y direction,  $F(2,22) = 0.311$ ,  $p = 0.736$ , or



variable error in the x,  $F(2,22) = 0.468$ ,  $p = 0.633$ , and y direction,  $F(2,22) = 1.410$ ,  $p = 0.265$ . The results indicate that the delay did not impact path length or final position when pointing to the center target.

#### Perturbed pointing trials

A total of 7.27% of the trials were not recorded because the marker was not visible or participants took longer than 3 s to complete their movement following the go signal. In addition to these trials, 4 trials (0.20%) were excluded from analysis because participants went straight to the correct target location without making a correction.

Participants corrected their movement to the appropriate target on  $82.2\% \pm 11.9$  SD of the remaining perturbed trials (see Table 4 for average error results). The error data revealed a main effect for Congruency,  $F(2,22) = 4.361$ ,  $p = 0.025$ , but post-hoc tests showed no significant difference between conditions. However, at the 50 ms delay, more errors were committed in the neutral condition compared to the congruent ( $p = 0.041$ ) and incongruent ( $p = 0.032$ ) conditions, Delay x Congruency:  $F(4,44) = 2.667$ ,  $p = 0.045$ . Once again, the percentage of correct responses supports the takeover criterion since the mask was able to take over the movement.

The influence of the prime at various points in the pointing trajectory was determined by looking at movement time, and the time, position, and resultant velocity data at the time of correction to the correct target location on trials in which participants completed their movement to the target indicated by the mask. Importantly, the final position in the x and y directions and corresponding variable errors were not affected by the delay between movement onset and prime onset ( $p > 0.05$ ). According to the initiation criteria, there should be a difference between the congruency conditions with respect to the various kinematic

variables examined. An influence of prime-mask congruency across all delays would also confirm that the primes can still exert an influence following various delays after movement onset. Although movement time and time of correction relative to movement onset should differ between congruent and incongruent conditions, these time variables should increase in all congruency conditions as the delay increased. In support of the independence criterion, we would expect that, when time locked to prime onset, the initial deviations in the average spatial trajectories (in Figure 6A) would be unaffected by the prime onset delay since the prime-mask SOA was constant. With respect to the variables derived from the average spatial trajectories, we would predict that the maximum horizontal position would not be influenced by the time delay; however, the time at which this value was achieved relative to movement onset should increase in the incongruent condition. Furthermore, the time when participants started pointing to the correct target should also increase linearly in all congruency conditions.

Once again, the movement time analysis supports the initiation criterion since the analysis revealed main effects for Mask,  $F(1,11) = 33.837, p < 0.001$ , Congruency,  $F(2,22) = 12.978, p < 0.001$ , and Delay,  $F(2,22) = 25.699, p < 0.001$ . MT was faster to the right target compared to the left target. Importantly, MT was significantly shorter in the congruent condition compared to the neutral,  $p = 0.002$ , and incongruent conditions,  $p = 0.001$ . As predicted, MT was significantly longer in the 50 ms condition compared to the 17 ms,  $p < 0.001$ , and 33 ms delay conditions,  $p = 0.004$ . The difference between the 17 ms and 33 ms delay conditions was also significant,  $p = 0.009$ .

Table 4

*Average errors (%), movement times (ms), time of corrections (ms) and velocity at correction (m/s) in Experiment 2 separated by Delay (17 ms, 33 ms, and 50 ms) and Congruency (Congruent (C), Neutral (N), and Incongruent (I)) with the associated standard deviation. The results are collapsed across the directional masks (Both) when no significant differences were observed between the left and right-pointing arrow masks.*

| Delay                           |       | 17 ms           |                 |                 | 33 ms           |                 |                  | 50 ms           |                 |                 |
|---------------------------------|-------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|
| Congruency                      | Mask  | C               | N               | I               | C               | N               | I                | C               | N               | I               |
| Errors (%)                      | Both  | 15.2<br>(15.9)  | 17.7<br>(19.2)  | 15.1<br>(16.2)  | 16.8<br>(13.9)  | 18.4<br>(17.4)  | 16.4<br>(14.3)   | 17.9<br>(16.6)  | 27.9<br>(19.6)  | 15.3<br>(15.7)  |
| Movement time<br>(ms)           | Left  | 636.7<br>(57.1) | 664.4<br>(69.1) | 668.3<br>(51.3) | 670.4<br>(39.0) | 684.0<br>(61.3) | 685.8<br>(56.2)  | 676.9<br>(51.7) | 698.0<br>(56.6) | 706.9<br>(55.6) |
|                                 | Right | 597.7<br>(59.1) | 618.6<br>(56.2) | 616.2<br>(63.2) | 611.9<br>(43.0) | 626.2<br>(62.1) | 634.9<br>(54.4)  | 623.3<br>(61.6) | 661.7<br>(62.8) | 665.2<br>(43.1) |
|                                 | Both  | 617.2<br>(60.2) | 641.5<br>(65.9) | 642.3<br>(62.3) | 641.1<br>(50.1) | 655.1<br>(67.2) | 660.3<br>(60.0)  | 650.1<br>(62.0) | 679.9<br>(61.4) | 686.1<br>(53.1) |
| Time of correction<br>(ms)      | Both  | 339.9<br>(34.2) | 357.8<br>(34.0) | 366.5<br>(30.7) | 355.9<br>(29.6) | 366.7<br>(36.3) | 377.9<br>(23.5)  | 367.9<br>(32.6) | 385.5<br>(36.8) | 397.9<br>(26.4) |
| Velocity at<br>correction (m/s) | Both  | 0.262<br>(0.14) | 0.216<br>(0.11) | 0.199<br>(0.10) | 0.218<br>(0.11) | 0.207<br>(0.12) | 0.179<br>(0.072) | 0.195<br>(0.09) | 0.168<br>(0.10) | 0.141<br>(0.08) |

Similar to the movement time data, the time, resultant velocity, and position associated with the time of correction also supports the initiation criterion regardless of the delay condition. With respect to time of correction, analyses showed a main effect for Congruency,  $F(2,22) = 17.772$ ,  $p < 0.001$ , and a main effect for Delay,  $F(2,22) = 34.190$ ,  $p < 0.001$ . The time of correction was significantly earlier in congruent trials compared to the neutral and incongruent trials,  $p = 0.014$  and  $p < 0.001$ , respectively. No differences were seen between neutral and incongruent trials,  $p = 0.159$ . Time of correction occurred sooner in the 17 ms Delay condition compared to the 33 ms,  $p = 0.002$ , and 50 ms Delay conditions,  $p < 0.001$ , and the time of correction in the 33 ms condition occurred significantly earlier than in the 50 ms condition,  $p = 0.005$ .

Participants' resultant velocity at the time of this correction showed a Mask x Congruency interaction,  $F(2,22) = 4.222$ ,  $p = 0.028$ . For the right mask, the congruent condition was significantly faster than the neutral,  $p = 0.005$ , and incongruent conditions,  $p = 0.011$ , whereas, for the left mask, the congruent condition was only significantly faster than the incongruent condition,  $p = 0.045$ . Additionally, there was a main effect for Delay,  $F(2,22) = 14.034$ ,  $p < 0.001$ . A post-hoc test on the factor of Delay revealed that the resultant velocity was significantly slower in the 50 ms condition compared to the 17 ms condition,  $p = 0.001$ . The 33 ms condition did not significantly differ from the 17 ms or the 50 ms conditions, both  $p > 0.061$ , but the linear trend was significant,  $F(1, 11) = 26.665$ ,  $p < 0.001$ .

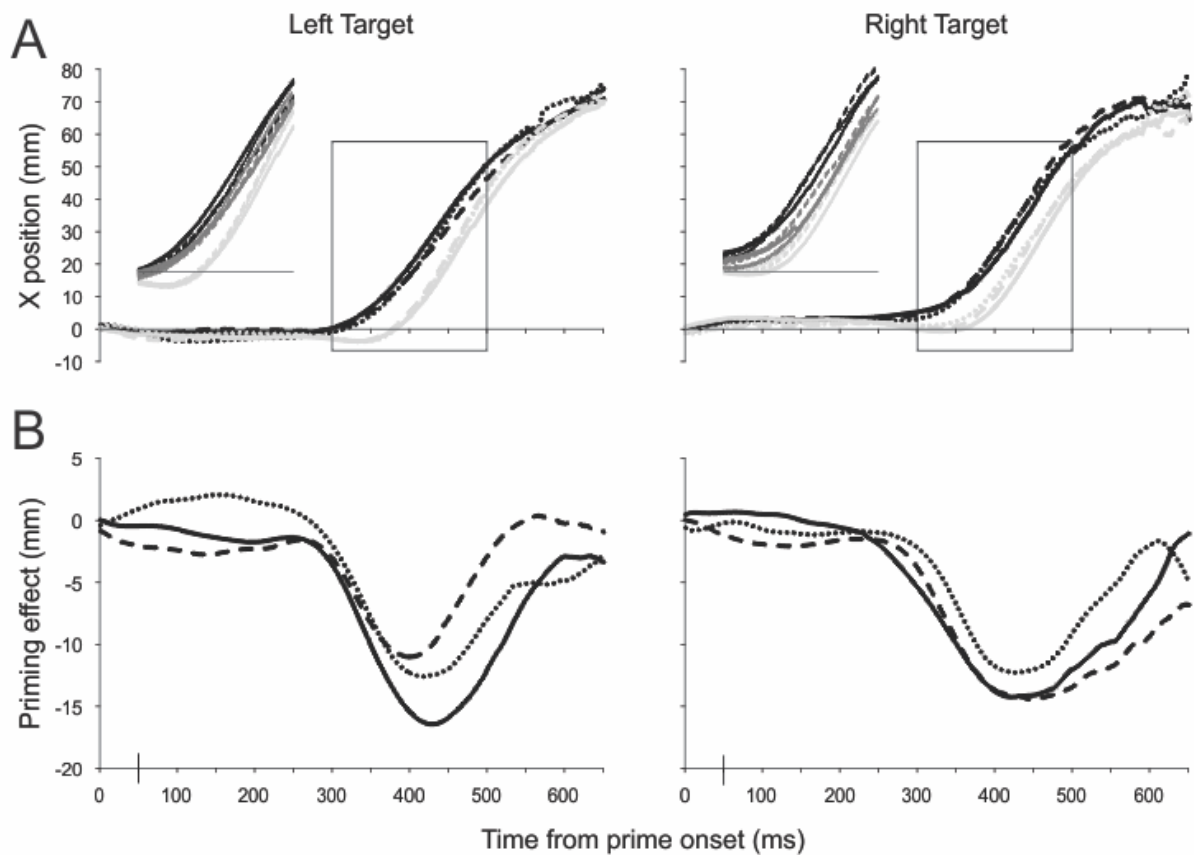
Similar to the velocity data, there was a significant Mask x Congruency interaction,  $F(2,22) = 15.514$ ,  $p = 0.002$ , for the horizontal position at the time of the correction to the appropriate target. For the right mask, participants' position in congruent and incongruent conditions differed significantly,  $p = 0.029$ , while the difference between the neutral and incongruent conditions approached significance,  $p = 0.053$ . For the left mask, the incongruent condition significantly differed from the congruent,  $p = 0.002$ , and the neutral conditions,  $p = 0.009$ . In sum, when participants started correcting their movement, they were closer to the correct target in the congruent and neutral conditions compared to the incongruent condition suggesting that the prime initially triggered its response resulting in a deviation in the incorrect direction in incongruent trials.

Taken together, analyses of the kinematic variables provide evidence that the prime was exerting an influence on the movement regardless of when it came on during the execution of the pointing task. Participants corrected and completed their movement later in incongruent trials as can be seen in Figure 6A. The prime also influenced the velocity and

position of the movement when participants started to correct their movement to the correct target.

Although the prime-mask SOA did not vary during Experiment 2, the data can still provide some insight with respect to the independence criteria of the rapid-chase theory. Specifically, the maximum horizontal position should be the greatest in the incongruent condition, but should not increase as the delay increases since the mask followed prime onset at a constant time of 50 ms. In addition, the time at which the maximum position was achieved should increase in incongruent trials relative to movement onset but remain the same for congruent and neutral trials.

However, these predictions are not fully supported by the analyses of the additional kinematic variables derived from participants' average lateral position over time, which are collapsed across directional masks since there was no significant main effect for Mask. While the position data supports the independence criterion, the time at which the maximum value is achieved does not. As predicted, the maximum position data revealed a main effect for Congruency,  $F(2,22) = 6.884$ ,  $p = 0.017$ , as the maximum position was greatest in the incongruent compared to the congruent condition,  $p = 0.008$ , and the factor of Delay was not significant,  $F(2,22) = 0.061$ ,  $p = 0.868$ . However, the time following movement onset at which the trajectory reached its maximum value did not increase linearly in the incongruent condition, Congruency x Delay:  $F(4,44) = 0.462$ ,  $p = 0.763$  (see Figure 5A and 5B).



**Figure 6. A)** The average spatial trajectory and **B)** the spatial priming effect (incongruent – congruent) when pointing to the left and right targets in Experiment 2 as a function of prime onset. The various lines represent the different congruency (congruent: black; neutral: dark gray; incongruent: light gray) and prime onset delay conditions (17 ms: dotted; 33 ms: dashed; 50 ms: solid). The vertical line on the x-axis indicates the time of mask onset. For clarity the neutral prime condition is excluded in the top figures but is presented from 300-500 ms in the inset. Positive values indicate movement in the correct direction while negative values indicate movement in the incorrect direction.

In all congruency conditions, it was expected that the time at which participants corrected their movement in the direction indicated by the mask should increase with an increasing delay relative to movement onset. Analysis supports this prediction since a significant main effect for Delay was found,  $F(2,22) = 15.575$ ,  $p = 0.001$ , as corrections in the 17 ms delay condition occurred significantly sooner than in the 33 ms,  $p = 0.020$ , and 50 ms conditions,  $p < 0.001$  (see Figure 5C). The difference between the 33 ms and 50 ms

conditions did not reach significance,  $p = 0.117$ . A main effect for Congruency,  $F(2,22) = 14.810$ ,  $p = 0.001$ , was also found since the congruent condition significantly differed from the incongruent ( $p < 0.001$ ) and neutral condition ( $p = 0.026$ ). Furthermore, the rapid-chase theory predicts that priming onset, the time when the priming function deviates from 0 indicating a difference between congruent and incongruent trials, should be similar across all delay conditions when time locked to prime onset. The amplitude of the different priming functions should be similar because the prime-mask SOA was constant. However, when examining Figure 6B it is evident that the spatial priming effects do not follow the independence criterion of the rapid-chase theory. The left and right spatial priming effects show a different pattern of results, as the order in which the different delay conditions deviate from the average time course is different. To the left target, the 17 ms Delay condition deviates from the average time course after the 33 ms condition while the 33 and 50 ms conditions deviate at approximately the same time when pointing to the right target. The onset of the priming effect does not appear to be tied to prime onset, as it does not reflect the timing of the input conditions. Although the maximum position and time of correction towards the correct target data supports the independence criterion, the time of the time of maximum horizontal position and priming effect data do not support the independence criterion.

In general, the results from Experiment 2 reveal that primes can influence the control of movements, when they are presented after a delay following movement onset, provided that sufficient time remains to execute a correction to the target location. Additionally, Experiment 2 supports the initiation and takeover criteria, but provides further evidence against the independence criterion during an ongoing movement.

### *Discussion*

The two experiments investigated the influence of the timing of prime and mask onset on the online control of pointing movements. Specifically, Experiment 1 was designed to test the predictions of the rapid-chase theory as it relates to movement execution. Previous pointing studies have shown support for the initiation and takeover criteria during movement execution but could not investigate the independence criterion because a fixed SOA was used. In order to determine if primes and masks are processed according to the rapid-chase theory during response execution, we manipulated the prime-mask SOA between 33, 50, and 67 ms which allowed us to determine if the data met the three criteria of the rapid-chase theory. It was hypothesized that the observed motor output would abide by the three criteria outlined in the rapid-chase theory, as has been shown in response initiation tasks (T. Schmidt et al., 2006; T. Schmidt & Schmidt, 2009; T. Schmidt & Seydell, 2008). In particular, the prime would dictate the initial portion of the movement (initiation criterion), such that, in incongruent trials, participants would deviate more in the incorrect direction compared to congruent trials. However, the mask would seize control of the movement so that the correct target was reached before the movement was completed (takeover criterion). Finally, the processing of the prime would initially be independent of the characteristics of the mask (independence criterion), such that the prime would have a greater influence (e.g., greater deviations in the incorrect direction) with increases in SOA.

The results from the current experiment support both the initiation and takeover criteria of the rapid-chase theory and replicate previous findings (Cressman et al., 2007, 2013; Fukui & Gomi, 2012), which have shown that a prime can influence the online control of movement before the mask exerts its control. However, the results do not support the



independence criterion, and thus refute the hypothesis that primes and masks are processed according to the rapid-chase theory during response execution. In particular it was found that the observed spatial priming effect was not the same as the theoretical spatial priming effect predicted by the independence criterion. According to the independence criteria of the rapid-chase theory, the shortest SOA should deviate from the average time course first and the longest SOA should deviate last with the intermittent SOA deviating after the first SOA but before the last SOA condition. As the results in Experiment 1 demonstrate, not only did the spatial priming effect not deviate in this predicted manner, but the deviation pattern was different when correcting to the two target locations. The 33 ms condition had a similar amplitude to the 50 ms SOA when pointing to the left target but had a similar amplitude to the 67 ms SOA when pointing to the right target. The argument that the independence criterion was not supported by the data in Experiment 1 is further substantiated by the findings of Experiment 2. In Experiment 2 the time that the primes were presented relative to movement onset was manipulated, while holding the prime-mask SOA constant at 50 ms. In this case, the rapid-chase theory would predict that the priming onset and amplitude of the priming functions would be the same for all three delay conditions when time locked to prime onset. The results failed to show the predicted time course since the priming onset for the different delay conditions occurred at different times relative to prime onset. In addition, when pointing to the left target, the 33 ms priming amplitude was smaller than the priming amplitude of the 17 ms condition but the 33 ms and 50 ms conditions had similar priming amplitudes when pointing to the right target. Although the results indicate that the prime can influence movement when presented after a delay following movement onset, the data does not abide by the independence criterion.

Previous studies in which prime-mask processing did not support the rapid-chase theory claimed that it was due to the short prime-mask SOA ( $< 30$  ms; T. Schmidt et al., 2006), task difficulty (T. Schmidt & Schmidt, 2009), or the occlusion of the prime stimulus by other distracting stimuli (F. Schmidt et al., 2014). Consequently, it was argued that recurrent processing was necessary to complete these tasks. It is unlikely that these explanations apply to the current situation because the prime-mask SOA was longer than 30 ms, the task did not require cognitive control in order to semantically process the prime since there was a direct relationship between the prime and response (Klapp, 2014), and the relevant features of the prime were not occluded. Nevertheless, this does not exclude the fact that fast recurrent processing could have occurred (Bullier, 2001) in the present paradigm, leading to the lack of large overt deviations at the longer SOAs. It is not surprising that the feedforward sweep elicited by the mask would have occurred faster than the one activated by the prime, since the mask would have been more salient than the prime given it was larger in size and more task-relevant, meaning it specified the required response (Lamme, 2004).

It was thought that the unconscious processing of the prime might differ between movement initiation and movement execution because of the increased mechanical ease of corrections (Christensen et al., 2008), the increased involvement of the dorsal stream (Milner & Goodale, 1995, 2008) or the decrease of the activation threshold during movement execution compared to movement initiation (Cressman et al., 2007). Specifically, it was thought that the prime would be processed faster during movement execution because it would have access to the dorsal stream which has been shown to be involved in the online control of action and does not necessitate conscious perception (Milner & Goodale, 1995, 2008). Moreover, according to the action trigger hypothesis (Kunde, Kiesel, & Hoffmann,

2003), the prime threshold is determined in advance by specifying action triggers (i.e., predetermined responses that are triggered following the processing of task relevant features of a stimulus) based on instructions and task goals, which reflect the participant's intentions to act in a certain manner in response to a specific stimulus. Thus, the amount of activation needed to trigger an action could differ depending on the task to be performed. In fact it was hypothesized that the activation threshold would be lower in a pointing task as suggested by Cressman et al. (2007) compared to a response initiation task. The current results suggest that there is a difference in unconscious processing between movement initiation and movement execution since the current data does not follow the rapid-chase theory but previous movement initiation studies have supported the rapid-chase theory (T. Schmidt et al., 2006; see also T. Schmidt et al., 2011 for a review). In contrast to our hypothesis, the prime activation threshold might have been increased instead of lowered during movement execution. Similarly, the use of a gating mechanism or the manner in which movements are controlled during flight could differ between movement initiation and execution.

The prime threshold might have been adjusted prior to movement due to prior experience. Consciously perceived positional errors (i.e., landing on the incorrect target in perturbed trials) or temporal errors (i.e., failure to meet the MT goal in direct pointing trials) from previous trials could have resulted in participants increasing the activation threshold needed to trigger a response to the onset of the prime stimulus in order to prevent unintentional errors. Processing fluency, the subjective feeling associated with the ease of processing information, could also have led to a modification of the prime activation threshold (Alter & Oppenheimer, 2009; Desender, Van Opstal, & Van den Bussche, 2014). This increased activation threshold following errors would lead to a decrease in the overt

deviations observed in response to the prime stimulus. Also the prime threshold might have been continuously updated during movement until the prime was presented such that the activation threshold was lower at the beginning compared to later in the movement. In other words, the prime would be able to exert a greater influence 17 ms after movement onset compared to 50 ms after movement onset. Although it is unlikely that the activation threshold was adjusted during movement in Experiment 1, it is possible that this threshold adjustment could partially account for the results in Experiment 2.

The use of a gating mechanism is another possibility that could explain why the rapid-chase theory does not apply to movement execution. Kiefer (2007) proposed a gating framework to explain the ability of an unconscious stimulus to elicit an automatic response. Kiefer suggested that primes are under preemptive control, such that top-down influences such as intention, task sets<sup>2</sup>, and attention can be established prior to prime onset to enhance or reduce the processing of the prime stimulus. In this situation, primes must be task-relevant as determined by the participants' established intentional goals and task sets in order to observe the priming effect. The specification of these top-down factors allow prefrontal areas to gate specific information processing pathways that are relevant to the task as specified by the top-down factors by modulating the gain of neurons (i.e., the probability at which a neuron's activation level will elicit a firing of a response). Neurons processing task relevant information have a higher gain in comparison to neurons processing task irrelevant information. Similarly, the extent of unconscious processing of a prime can be gated such that primes can be further processed or blocked by a pathway (Kiefer, 2007). For example, in

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<sup>2</sup> Kiefer (2007) distinguishes between the concepts of intention and task sets. He defines a task set as being "the immediate computational consequences of pursuing a current goal during task performance" while intention is more general as it encompasses both "the conscious representation of the goal and the subjective state of commitment to perform a goal-related action" (Kiefer, 2007, p.299).

high conflict environments such as when a larger proportion of trials are incongruent, the gating mechanism decreases the processing of the prime leading to a decrease in the automatic response to the prime. In sum, the effect of the prime is attenuated in high conflict situations because it increases the number of errors, and therefore is given less access to automatic pathways by modulating attention prior to stimulus onset.

The adjustment of the prime activation threshold and the gating mechanism may explain the current results. In support of these two accounts, it has been proposed that control strategies decrease the prime's influence in high conflict situations such as when the preceding trial was incongruent (Desender, Van Lierde, & Van den Bussche, 2013; van Gaal, Lamme, & Ridderinkhof, 2010; see Ansorge, Kunde, & Kiefer, 2014 and Kunde et al., 2012 for a review) or when a greater proportion of incongruent trials were presented (Bodner & Lee, 2014; Jaśkowski, Skalska, & Verleger, 2003; Wolbers et al., 2006; see Ansorge et al., 2014 and Kunde et al., 2012 for a review). In these situations, the priming effect was smaller suggesting that participants employed a control strategy, such as increasing the prime activation threshold or using a gating mechanism, in order to decrease the number of errors in a high conflict situation. In the current experiments, only 33% of the perturbed trials were congruent (11% of all trials). Consequently, for optimal performance it would have been beneficial to limit the amount of control exerted by the prime because, in perturbed trials, the prime was mainly task-irrelevant in the sense that it did not indicate the target location. On the other hand, it could be argued that the neutral prime and neutral mask condition was congruent; thus, increasing the percentage of congruent trials (78% of all trials). The argument that direct pointing trials were treated as congruent is supported by the finding that a greater number of errors in the perturbed trials occurred with a neutral prime suggesting

that it was activating a response to the center target. Although the direct pointing trials could be argued to be congruent trials, the presentation of the neutral prime before the neutral or directional mask should not have altered participants' original intentions because they were asked to initiate their movement to the center target; therefore, the neutral prime did not specify a new response but was in line with the current and most common response.

According to Klapp (2014), a stronger stimulus-response binding would be established between the neutral prime and a response to the center target because all neutral masks were preceded by a neutral prime leading to direct response priming. Hence, the directional primes would not elicit as strong a response to the center target as the neutral prime. Klapp's (2014) automatization account is in contrast to the action-trigger hypothesis since Klapp proposed that direct response priming results from the automatization of the stimulus and response links and not from intentional control. Evidence favouring the automatization account of response priming has shown that conscious strategies seem to only be used when the prime is visible since conflict experienced in the previous trial with a masked prime did not lead to a decrease in the priming effect but when the previous trial presented a visible prime a decrease in the priming effect was observed (Ansorge, Fuchs, Khalid, & Kunde, 2011; Frings & Wentura, 2008; Greenwald, Draine, & Abrams, 1996; Kunde, 2003). These results suggest that the prime must be visible in order to engage control strategies to decrease the processing of the irrelevant features of the prime stimulus. While the prime activation threshold and gating mechanism accounts could explain the current data, if invisible primes do not invoke control strategies then the current results are not likely due to changes in the activation threshold of the prime or its access to specific processing pathways.

On the other hand, the current data may not obey the rapid-chase theory, not because the visual processing of the prime and mask did not occur in a strict feedforward manner, but because of the way online movements are controlled. According to the minimal intervention principle (Liu & Todorov, 2007; Todorov & Jordan, 2002), movements that deviate from the average trajectory are only corrected if they impede performance. To minimize effort, accuracy is prioritized in the task relevant direction allowing for variability in the task-irrelevant dimension (Todorov & Jordan, 2002). In the present experiment, deviations in the horizontal direction might only become task relevant once the mask appears, specifying the target location. Therefore, the system does not concern itself with these minimal errors due to sensory and motor noise because it might have to correct the movement later in this direction once the mask appears indicating which target to land on. Nevertheless, once the pointing trajectory exceeds an allowable margin of error, an adjustment is executed based on the person's intention, meaning the prime can only control overt deviations to a certain extent determined by the goals of the task. Similarly, Oostwoud Wijdenes, Brenner, & Smeets (2011) found that the intensity of a correction depends on the time remaining until the movement is complete. As a result, early corrections and late corrections occurred with a similar latency of correction but late corrections were made with a greater intensity providing additional evidence that corrections are executed differently as the movement progresses. Possibly the greater correction intensity in response to the mask might have obscured the influence of the prime on movement trajectory because the prime was presented before the mask.

The trajectory deviations observed in the current study might have occurred because the moving hand was hidden from view. The inability to see the moving limb during

movement could also explain why movement time and time of correction (Reichenbach, Thielscher, Peer, Bühlhoff, & Bresciani, 2009) were longer in the current study compared to previous studies using a similar experimental set-up where the hand was visible (Cressman et al., 2007, 2013). Our MT goal also allowed for longer movement durations. However, in Experiment 2, MT in direct pointing trials increased as the delay increased suggesting that participants might have been waiting for the onset of the mask stimulus before completing their movement to the center target.

Overall, the present results reveal that the prime is able to influence a movement even if it is presented at various time points following movement onset and the mask can take over control of the movement as long as there is sufficient time to make a correction. While these results support the first two tenets of the rapid-chase theory, the prime does not appear to be initially processed independently from the mask as suggested by the third tenet (independence criterion). Thus, the results do not support the application of the rapid-chase theory to ongoing movements which means that determining whether or not the prime and mask are processed in a feedforward manner cannot be resolved by simply observing the behavioural output of the motor system. The prime and mask may still be processed in a feedforward manner but fast recurrent processing, modifying the prime activation threshold, gating the prime's access to certain pathways or controlling movements in a certain manner could have prevented feedforward processing or reduced the impact of the prime leading to smaller movement deviations. All these explanations deserve further exploration using a reaching task since it has the potential to provide a greater insight into the inner workings of the decision making process and the automatic processing of subliminal primes.



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### **Chapter III: General Discussion**

The two experiments examined the time course of the priming effect during an ongoing movement to determine if the criteria outlined by the rapid-chase theory could extend to movement execution and be used to determine if the processing of the prime stimulus occurred in a feedforward manner based on the observed output of the motor system. Namely, the aim of Experiment 1 was to determine if the motor output abided by the independence criterion since previous studies have provided support for the initiation and takeover criterion but the use of a constant prime-mask SOA prevented the further analysis of the data with respect to the independence criterion. Experiment 2 aimed to extend the initiation and takeover criteria of the rapid-chase theory when the prime was presented at various time points during movement. In contrast to hypotheses, the results do not support the application of the rapid-chase theory to movement execution since the spatial priming effect did not follow the expected time course that would be predicted if the prime was strictly processed independently from the mask. Participants, most likely, adapted a control strategy, based on prior experience, to decrease unwanted spatial and temporal errors. This control strategy could have involved increasing the prime activation threshold needed to trigger a response or gating the access of the prime to motor processing pathways. Although the current study cannot differentiate between these different control strategies, the following section will discuss specific shortcomings of the current studies and ways in which future studies can address these limitations to provide further insight into the use of control strategies and the extent of unconscious processing on the online control of movements.

Previous studies (Bodner & Lee, 2014; Cheesman & Merikle, 1986; Jaśkowski, Skalska, & Verleger, 2003; Merikle & Joordens, 1997; Wolbers et al., 2006) have shown that the

probability of congruent and incongruent trials can limit the influence of the masked prime.

It is currently unclear if the proportion of trials in which a correction is required impacts the priming effect. Specifically, would an increase in the proportion of corrections to the eccentric targets increase the likelihood of making a response in the direction of the prime and would this be modulated by the percentage of congruent and incongruent trials? To address this question, the proportion of corrections to the outer targets could be increased to 50% or 75% instead of 33%, which was used in the current experiments. Furthermore, a situation in which 100% of the trials require a correction to the left or right targets would allow for a direct comparison between the percentage of congruent and incongruent trials during a pointing task. By eliminating movements to the center target, all trials must be completed to the left or right target resulting in the star-shaped prime being truly neutral as it would not specify a response. In addition, intermixing masked and visible primes would allow for a comparison of control strategies when the conflict elicited by incongruent primes is consciously perceived. The rapid-chase theory would still predict that the initial pointing trajectory would be dictated by the visible prime because the prime is initially processed as a feedforward sweep triggering its associated response. These potential studies are needed to further investigate the extent of control strategies in response priming paradigms to better understand the limits of unconscious processing and provide support for either the action-trigger hypothesis or the automatization account which have been mainly supported by RT tasks. By conducting studies using a pointing task, the prime's influence on cognitive control functions are captured through the unfolding of the decision making process during movement.

The current experiments were the first to investigate how the prime-mask SOA and the delay between movement and prime onset affect the priming effect. Nonetheless, additional studies are required to confirm and extend these findings. For example, in the current study we were unable to assess the influence of directional primes when they preceded the neutral mask. This raises the question of whether or not directional primes result in overt deviations despite the mask indicating to continue the movement as planned to the center target. The rapid-chase theory predicts that, in this situation, we should still observe an initial deviation in the direction of the prime because the prime would be processed as a fast feedforward sweep leading to an activation of its associated response before the mask is able to exert its control on the movement. In fact, a recent pilot study conducted in our laboratory indicated that directional primes do influence the pointing trajectory even though they preceded a neutral mask as evidenced by the participants' endpoint position in the lateral direction. In comparison to the endpoint position with a neutral prime, participants landed slightly more leftward following a left prime and slightly more rightward following a right prime. While these results agree with the rapid-chase theory that movements are influenced by the prime and mask, we found that SOA did not have an effect on final position. This suggests that the prime did not lead to greater deviations as the SOA increased which is contrary to the predictions of the independence criterion.

Another limitation of the current study pertains to the prime identification task. It is important to conduct the prime identification task in the same context and with the same stimuli parameters (e.g., prime duration, prime-mask SOA) as the pointing task (Lin & Murray, 2014; F. Schmidt et al., 2011; T. Schmidt & Vorberg, 2006) to avoid confounding variables such as task difficulty (Pratte & Rouder, 2009). Although the prime identification

task tested prime visibility at the three prime-mask SOAs, participants did not execute a movement; therefore, timing of prime onset was different in the prime identification task than in the pointing task of Experiment 1 and Experiment 2. In fact, visual processing may be enhanced during movement (Tremblay & Nguyen, 2010) resulting in an underestimation of prime visibility in the prime identification task. Nevertheless, Cressman et al. (2013) tested prime visibility at movement onset while having participants complete a pointing movement and results indicated that participants were still unable to accurately differentiate between the directional primes but a disadvantage of this method is that attention is divided between the two stimuli. The division of attention might reduce the participants' ability to consciously report the identity of the prime, once again, resulting in an underestimation of prime visibility (Lamme, 2004; F. Schmidt et al., 2011). Considering attention has also been found to modulate the priming effect in previous studies (Naccache, Blandin, & Dehaene, 2002; F. Schmidt & Schmidt, 2010; T. Schmidt & Seydell, 2008), future studies could examine the presence of an attentional cue presented during movement but before stimulus onset to investigate attentional modulation of the priming effect during movement. The current experiment did not involve a reaction time task, enabling participants to initiate their movement freely after the go-signal. Consequently, the prime and mask did not appear at a fixed time interval relative to the go-signal. In fact, the prime and mask could appear up to 3 s after the go signal potentially resulting in a smaller priming effect because the masked prime was unattended on some trials.

Finally, it is important to note that not all prime deviations may have been detected since the criterion to classify a trajectory as having overtly deviated might have been too stringent to detect smaller deviations away from the average spatial trajectory based on

positional data. Methods such as the extrapolation method used by Veerman, Brenner, & Smeets (2008) and Oostwoud Wijdenes, Brenner, & Smeets (2011) might be better able to determine accurately the latency of small corrections induced by the prime stimulus.

Oostwoud Wijdenes, Brenner, & Smeets (2014) recently performed a simulation study and showed that applying the extrapolation method to the average acceleration data, in comparison to threshold and confidence interval methods, led to the most accurate and precise results while being the least affected by the intensity of corrections.

In summary, the results do not support the independence criterion, and hence the use of the rapid-chase theory in determining the feedforward processing of the prime and mask based on the observed motor behaviour. Although the rapid-chase theory has been supported by studies presenting the prime during movement initiation, the current study presented the prime during movement execution which further suggests that differences exist between movement initiation and movement execution. The results of the current experiments highlight the importance of further investigating the limits of the rapid-chase theory and the degree of unconscious processing of visual stimuli during movement execution.

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## Appendix A

### Edinburgh Handedness Inventory<sup>1</sup>

Name: \_\_\_\_\_

Date: \_\_\_\_\_

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks. Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓). If you are indifferent, put one check in each column (✓|✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

| Task / Object                                                                                         | Left Hand            | Right Hand |
|-------------------------------------------------------------------------------------------------------|----------------------|------------|
| 1. Writing                                                                                            |                      |            |
| 2. Drawing                                                                                            |                      |            |
| 3. Throwing                                                                                           |                      |            |
| 4. Scissors                                                                                           |                      |            |
| 5. Toothbrush                                                                                         |                      |            |
| 6. Knife (without fork)                                                                               |                      |            |
| 7. Spoon                                                                                              |                      |            |
| 8. Broom (upper hand)                                                                                 |                      |            |
| 9. Striking a Match (match)                                                                           |                      |            |
| 10. Opening a Box (lid)                                                                               |                      |            |
| Total checks:                                                                                         | LH =                 | RH =       |
| Cumulative Total                                                                                      | CT = LH + RH =       |            |
| Difference                                                                                            | D = RH – LH =        |            |
| Result                                                                                                | R = (D / CT) × 100 = |            |
| Interpretation:<br>(Left Handed: R < -40)<br>(Ambidextrous: -40 ≤ R ≤ +40)<br>(Right Handed: R > +40) |                      |            |

<sup>1</sup> Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9, 97-113.



## Appendix B

File Number: H05-10-11

Date (mm/dd/yyyy): 07/03/2014



**Université d'Ottawa**  
Bureau d'éthique et d'intégrité de la recherche

**University of Ottawa**  
Office of Research Ethics and Integrity

### Ethics Approval Notice Health Sciences and Science REB

#### Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

| <u>First Name</u> | <u>Last Name</u> | <u>Affiliation</u>               | <u>Role</u>            |
|-------------------|------------------|----------------------------------|------------------------|
| Erin K.           | Cressman         | Health Sciences / Human Kinetics | Principal Investigator |
| Jenna             | Flannigan        | Health Sciences / Human Kinetics | Student Researcher     |
| Sajida            | Khanafer         | Health Sciences / Human Kinetics | Student Researcher     |
| Neil              | Drummond         | Health Sciences / Human Kinetics | Research Assistant     |
| Jesse             | Lombardo         | Health Sciences / Human Kinetics | Research Assistant     |
| Ruth              | Posthuma         | Health Sciences / Human Kinetics | Research Assistant     |
| Basel             | Zbib             | Health Sciences / Human Kinetics | Research Assistant     |

**File Number:** H05-10-11

**Type of Project:** Professor

**Title:** Sensory Integration and Motor Learning

| <b>Renewal Date (mm/dd/yyyy)</b>                    | <b>Expiry Date (mm/dd/yyyy)</b> | <b>Approval Type</b> |
|-----------------------------------------------------|---------------------------------|----------------------|
| 06/24/2014                                          | 06/23/2015                      | Ia                   |
| (Ia: Approval, Ib: Approval for initial stage only) |                                 |                      |

**Special Conditions / Comments:**  
N/A

## Appendix C



### INFORMED CONSENT OF PARTICIPANT

Research involving human subject require written consent of the participants.

I, \_\_\_\_\_, hereby volunteer to participate as a subject in the study entitled “Sensory integration and motor learning”. I have read the information presented in the above background information and I had the opportunity to ask questions to the investigators. I understand that my participation in this study, or indeed any research, may involve risks that are currently unforeseen.

I recognize that there will be no direct benefit to me from my participation in this study.

I understand that if I have any questions regarding the study, I may contact Dr. Erin Cressman at 613-562-5800 ext 4264. If I have any questions or complaints with regards to the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5, tel.: 613-562-5387, email: [ethics@uottawa.ca](mailto:ethics@uottawa.ca).

I have been given a copy of this Background Letter and Consent Form for me to keep.

Signature of participant: \_\_\_\_\_ Date: \_\_\_\_\_

Signature of Researcher: \_\_\_\_\_ Date: \_\_\_\_\_