THE INTERPLAY OF ELABORATE SUBLIMINAL PROCESSING AND COGNITIVE CONTROL

A Dissertation

by

KUNCHEN XIAO

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Takashi Yamauchi
Committee Members,	Darrell Worthy
	Lisa Geraci
	Louis Tassinary
Head of Department,	Heather Lench

August 2016

Major Subject: Psychology

ABSTRACT

This dissertation investigates how cognitive control influences subliminal semantic processing. Unlike the traditional view that unconscious processing is stereotypical and independent of cognitive control, recent evidence shows that unconscious processing can be elaborate and flexible. Subliminal processing can occur at a semantic level and be modulated by top-down attention. On this basis, the temporal attention window theory and global workspace theory are proposed to explain the interaction between cognitive control and subliminal processing, arguing that the top-down attention is necessary for elaborate subliminal processing. However, the reported absence of priming in near absence of attention could be attributed to the insufficient sensitivity of the response time measure. To clarify the role of top-down attention in subliminal semantic processing, five experiments were conducted to assess semantic priming with a cursor motion method and investigate the role of top-down attention in elaborate subliminal processing.

These experiments demonstrated that semantic priming could be reliably assessed by cursor motion measures such as the area under the curve (AUC). By directly comparing the AUC measure with the conventional response time measure (RT), larger priming effects were found for the AUC data than the RT data, suggesting that the AUC was more sensitive than the RT to semantic priming. Also, by applying the cursor motion method to numeric comparison tasks, the necessity of attention in subliminal semantic processing was examined. Results showed that top-down attention helped subliminal semantic processing, but semantic priming was still significant in near absence of attention. In addition, the influence of cue colors on semantic priming was examined; results indicated that priming effects elicited by cue colors were limited. Furthermore, the stimulus-onset asynchrony (SOA) was manipulated to investigate the time course of top-down attention and subliminal semantic processing. It was found that top-down attention extended the lifespan and amplified the magnitude of subliminal semantic processing, suggesting that the temporal attention window lasts for more than 1000ms. Taken together, it can be concluded that assistance from top-down attention prolongs and magnifies semantic priming yet may not be necessary for elaborate subliminal processing.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Takashi Yamauchi, and my committee members, Dr. Geraci, Dr. Tassinary, and Dr. Worthy, for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the undergraduate research assistants who helped me conduct experiments and collect data, without which this work would not be possible, and to all the undergraduate students who were willing to participate in the study.

Finally, thanks to my mother and father for their support and love.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The relationship between conscious and unconscious processing has been long discussed. A classic view is that consciousness and unconsciousness respectively have distinct features: conscious processing is effortful, elaborate, and flexible while unconscious processing is stereotypical, superficial, and independent of cognitive control (Koch & Crick, 2001; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). This view, however, is challenged by emerging evidence that unconscious processing is elaborate enough to handle relatively complex tasks such as lexical decision, conceptual categorization, numeric judgment, and picture comprehension (Opstal et al., 2010, 2011). Also, unconscious processing is flexible and modulated by cognitive control (Naccache et al., 2002; Dehaene et al., 2005).

This dissertation investigates how elaborate subliminal processing and cognitive control interact. The introduction first reviews studies corroborating the idea of *elaborate* subliminal processing: subliminal processing can occur at a semantic level. The following section discusses further evidence that subliminal semantic processing is influenced by cognitive control such as top-down attention, which reveals the flexible nature of subliminal processing. The third section discusses potential problems of previous studies and proposes feasible solutions.

1.1 Evidence for Elaborate Subliminal Processing

Early studies (Dixon, 1971; Marcel, 1983; Fowler, Wolford, Slade, & Tassinary, 1981; Tassinary, Orr, Wolford, Napps, & Lanzetta, 1984) suggest that semantic processing can be activated without awareness. For example, Fowler and colleagues showed that the lexical relatedness between a masked priming word and a target word influences participants' detection of the target word in absence of awareness (Fowler et al., 1981); similarly Dixon (1971) demonstrated that the affective valence of masked primes modulates participants' perceptual judgment of targets. Other studies also indicate that the awareness of masked stimuli has little influence on semantic or affective priming effects (Marcel, 1983; Tassinary et al., 1984).

In a typical word-detection task, participants pressed a key as soon as they detected any word, preceded by another briefly presented masked word (i.e., prime). It was found that when the priming word and target word were semantically incongruent, participants' responses were delayed; subsequent awareness tests showed that when participants were asked to respond to the masked priming word, the accuracy was at a chance level, suggesting that the observed semantic priming was subliminal (Fowler et al., 1981).

Based on these findings, it has been suggested that semantic processing of subliminal stimuli is automatically activated, and such activation diffuses through neural circuits, leading to semantic priming. According to the spreading activation theory (Anderson, 1983; Collins & Loftus, 1975; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), conscious and unconscious processing has distinct features; conscious processing is controlled by attention and can only focus on limited information, while unconscious processing is parallel and can handle multiple features of stimuli at one time. The involvement of awareness may even impede subliminal processing because the selective mechanism of attention works against the diffuse nature of subliminal processing. Thus, consciousness is more likely to restrict rather than assist subliminal processing (Dixon, 1971).

Nevertheless, a few problems undermine the claims of "subliminal semantic processing." First, some lexical decision tasks do not necessarily activate semantic processing. For example, in an orthographical judgment task, participants judged whether a letter string was a word or non-word and responded as quickly and accurately as possible by pressing a key. The target letter string was preceded by another masked letter string (i.e., prime), which was either a word or non-word. It was found that participants responded faster when the prime and target words matched (i.e., both were words or non-words) (Dixon, 1971). However, because participants received identical word / non-word trials so many times, they could easily distinguish a word (e.g., final, modal) from a non-word (e.g., midet, kinep) without retrieving the meaning of words. For example, participants could quickly recognize "final" as a word without recalling the meaning of "end," "last," etc.; similarly, they could categorize "kinep" as a non-word simply because they were unable to recognize it, without thinking of the meaning. Thus in this task, the observed priming could have occurred at a relatively superficial level rather a semantic level (Damian, 2001). Second, some masked priming studies did not assess participants' awareness of masked stimuli in a rigorous way. For example, Wickens (1972) instructed participants to report masked priming words in the awareness test and found that participants could not correctly report the primes. Such self-report test underestimates participants' awareness because the inability to report a masked word does not guarantee that the word is invisible. Third, the sample sizes in many studies are small (e.g., 10-20 participants).

To remedy these problems, Dehaene et al. (1998) asked participants to perform semantic judgment directly on targets and applied a more rigorous method to assess participants' awareness of masked primes. Their results showed that people could unconsciously judge whether a target number (e.g., "6") was smaller or larger than five. The target number was preceded by a briefly presented (43ms) masked prime word (e.g., "ONE"). It was found that when the target and prime were both smaller (or larger) than five (i.e., "congruent" trials), the response time was shorter than that of incongruent trials. Similar studies have reported that participants can also judge whether two subliminal letters are semantically identical or not. (Van Opstal et al., 2008; Van Opstal, Calderon, Gevers, & Verguts, 2011). Such subliminal priming phenomena, known as the "congruency effect," corroborate unconscious semantic processing (See also Van Opstal, Moors, Fias, & Verguts, 2008; Van Opstal, Reynvoet, Verguts, 2005).

Evidence for unconscious semantic processing is based on the "masked priming" paradigm: a sequence of stimuli is rapidly presented, and participants respond to targets preceded by masked primes. Trials where the prime and target point to the same response are "congruent," otherwise "incongruent." Shorter response latency in congruent trials than that in incongruent trials is called the "congruency effect." After the experimental task, an awareness test is given to assess the visibility of masked primes. Trials in the awareness test are identical to those in the experimental task; however, participants are explicitly informed of the masked primes and instructed to respond to the primes rather than the targets (Greenwald, Draine, & Abrams, 1996).

Based on the masked priming paradigm, subliminal semantic processing is observed in conceptual categorization. For example, participants can judge whether a masked target word is pleasant or unpleasant (Abrams, Klinger, & Greenwald, 2002) and conceptually categorize a word without awareness (Klauer, Eder, Greenwald, & Abrams, 2007; Spruyt, Houwer, Everaert, & Hermans, 2012). Not only numbers and words, visually complex stimuli such as pictures can also be subliminally processed at a semantic level: participants can judge whether a masked picture is an artificial or natural object (Dell'Acqua & Grainger, 1999; Van den Bussche, Notebaert, & Reynvoet, 2009) or whether a masked face is famous or not subliminally (De Gardelle, Charles, & Kouider, 2011). Such congruency effects for subliminal pictures was also replicated when participants were prompted to judge the gender of face pictures, where participants responded faster when both the prime face and target face belonged to the same gender. The same pattern was observed when the task was to judge the race of faces. (Amihai, Deouell, & Bentin, 2011).

In addition to semantic information, the subliminal pictures can also be processed at an affective level. For example, Gobbini, Gors, Halchenko, Hughes, & Cipolli (2013) found that angles of masked faces influenced participants' detection of faces. When the face was staring at participants rather than with a biased angle, people detected the face faster, suggesting that participants can unconsciously detect threatening cues such as a face staring at you. Furthermore, Kiesel and Kunde (2009) found that experts could even “play chess unconsciously”: experts could unconsciously judge whether a piece of chess was a configuration of “Check” or “Non-Check.”

To summarize, subliminal stimuli can be processed in an “elaborate” manner, which challenges the traditional view that subliminal processing is superficial (Dehaene et al., 1998; 2005). Evidence further suggests that subliminal processing is flexible rather than stereotypical: cognitive control such as top-down attention influences subliminal processing, which will be discussed in the next section.

1.2 Cognitive Control Influences Elaborate Subliminal Processing

A typical form of cognitive control is top-down attention, which is the cognitive process of allocating limited processing resources and selectively concentrating on a discrete aspect of information while ignoring other perceivable information. Though attention is often confounded with consciousness, they are not identical. For example, attention to invisible stimuli influences subliminal processing (Dehaene et al., 2006). A traditional view is that subliminal semantic processing is autonomous and independent of cognitive control (Schneider & Shiffrin, 1977). However, recent studies suggest that two types of top-down attention modulate subliminal processing: feature-specific attention and temporal attention (Koch, & Tsuchiya, 2007; Cohen, Cavanagh, Chun, & Nakayama, 2012).

Feature-specific attention, which is elicited by manipulating task demand, is the phenomenon that only attended semantic features of masked stimuli can be subliminally processed while unattended features are ignored. For example, participants perform either one of two judgment tasks: 1) judging whether a target word belongs to the "human" or "non-human" category and 2) judging whether a target word is affectively positive or negative. In both cases, each target is preceded by a masked priming word. Interestingly, the same "friend (prime) – snob (target)" trial is often perceived as congruent in a "human / non-human" judgment whereas incongruent in a "positive / negative" judgment. This suggests that when participants attend to affective features of stimuli (i.e., positive / negative), categorical features of masked stimuli (i.e., human / non-human) are not processed, vice versa (Spruyt et al., 2012). Similar results were found when participants made a phonological judgment (i.e., bisyllabic or not) of target words; subliminal congruency effects were observed for phonological congruency but not for categorical congruency (i.e., "living" or "non-living"), vice versa (Weibel, Giersch, Dehaene, & Huron, 2013). Clearly, subliminal processing is modulated by cognitive control manipulated by task demand (see also Kiefer & Martens, 2010; Kouider & Deheane, 2007; Spruyt, De Houwer, & Hermans, 2009).

Temporal attention is a top-down attention window that lasts for a few hundred milliseconds; it can be manipulated by randomly varying the time frame of stimuli. In the Naccache et al. study (Naccache, Blandin & Dehaene, 2002), participants judged whether a target number (e.g., "9") was larger or smaller than five, preceded by a masked prime number (e.g., "6"); participants' top-down attention was manipulated by occasionally presenting a visual cue. The pre-prime duration changed randomly from trial to trial to disrupt participants' top-down attention because it was impossible to predict exactly when a target number would appear. In a cued condition, however, a green square cue was presented for 200ms to signal an upcoming target number, facilitating participants' top-down attention (the interval between the cue and target was fixed at 584ms). Uncued and cued trials were mixed and presented in a random order. Results showed that subliminal congruency effects were present only in the cued condition but not in the uncued condition. On this basis, Naccache et al. (2002) argue that top-down attention is *necessary* for subliminal semantic processing: when participants saw the cue and knew the target was coming, they opened a temporal attention window lasting for hundreds of milliseconds, which amplified subliminal semantic processing. In contrast, subliminal primes not covered by the temporal attention window in the uncued condition elicited no semantic processing.

In brief, subliminal semantic processing is absent in near absence of attention; masked primes not covered by the temporal attention window cannot elicit semantic priming. In other words, assistance from top-down attention is the prerequisite for elaborate subliminal processing. This notion is supported by other studies such as participants correctly reporting locations of subliminal visual stimuli only when top-down attention is present (Hsieh, Coals, & Kanwisher, 2011), and subliminal comprehension of natural scenes requires the assistance of top-down attention (Cohen, Alvarez, & Nakayama, 2011).

Dehaene and colleagues further argue that for elaborate subliminal processing to occur, it must be amplified by top-down attention (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). The global workspace theory (Dehaene et al., 1998; Dehaene

& Naccache, 2001; Dehaene & Changeux, 2011) explains the underlying mechanisms for the interaction between subliminal processing and top-down attention. This theory, which is developed from the Norman and Shallice (1980) model and the Baars (1989) model, differentiates two major computational spaces in the brain. One is a peripheral processing space, which is composed of a set of modular, autonomous, and parallel processors. These processors are functionally specialized; they work for perceptual and semantic processing. Each modular processor is implemented by a specialized, hard-wired network of interconnected cortical neurons.

The other is the global workspace consisting of cortical neurons distributed in the prefrontal and parietal cortices; these cortical neurons receive information from peripheral modular processors and send the information back to the peripheral processors through long-range excitatory and inhibitory axons. The major function of the global workspace is to coordinate the peripheral modular processors by strengthening or suppressing their activities. This gating mechanism, which is implemented by descending modulatory projections from global workspace neurons to peripheral modular processors, is essential for cognitive control — those projections selectively amplify or suppress the ascending inputs from peripheral processors.

The peripheral modular processors are classified into five categories: long-term memory circuits, perceptual circuits, evaluation circuits, motor programming circuits, and attention circuits, among which the attention circuits allow the global workspace to selectively amplify or attenuate signals from peripheral modular processors. The autonomous activities executed by peripheral processors explain spontaneous elaborate processing without consciousness or attention: some modular processors are specialized in elaborate processing such as semantic categorization, numerical representation, face recognition, scene comprehension, among others. These processors automatically process inputs and send outputs to the global workspace. Some outputs are not salient enough to gain relevant cognitive resource in the global workspace and are ignored by top-down attention. Although various peripheral processors project to the global workspace, only a subset of inputs can access it.

If the autonomous activities of a peripheral processor are not amplified by top-down attention, the processing will fade away quickly in the global workspace. Otherwise, attended autonomous activities gain more cognitive resource in the global workspace, which results in amplified subliminal priming. Cognitive control is a fundamental function of the global workspace, which selectively lifts some autonomous processors while suppressing others. For example, a task asking for affective evaluation rather than semantic categorization induces the global workspace to allocate cognitive resource to process affective rather than semantic features of subliminal stimuli. This reciprocal relationship amplifies affective priming while suppressing semantic priming.

The global workspace theory articulates the interplay of cognitive control and elaborate subliminal processing. However, this theory emphasizes the necessity of top-down attention to enable elaborate subliminal processing: semantic processing of subliminal stimuli requires at least a minimum amplification by top-down attention, without which subliminal stimuli are not processed at a semantic level. This view, however, is challenged by the counterevidence demonstrating that subliminal semantic priming occurs in near absence of top-down attention, which will be discussed in the next section.

1.3 Is Top-down Attention Necessary for Elaborate Subliminal Processing?

Although top-down cognitive control, such as feature-specific attention and temporal attention, modulates elaborate subliminal processing, an unanswered question is whether elaborate subliminal processing can occur without assistance from top-down attention.

Other than the evidence for the necessity of attention in subliminal semantic priming (Naccache et al., 2002; Dehaene et al., 2005, 2006; Spruyt et al., 2009, 2012), there is counterevidence suggesting that elaborate subliminal processing occurs in near absence of attention. For example, pictures can be comprehended in near absence of attention: participants accurately report the gist of masked photographs and the gender of masked faces, which are briefly presented on unattended peripheral locations (Li, VanRullen, Koch, & Perona, 2002; Reddy, Wilken, & Koch, 2004). Also, in a numerical comparison task, subliminal primes influence participants' numerical judgment in near absence of attention (Rahnev, Huang, & Lau, 2012; Heinemann, Kunde, and Kiesel, 2009). These studies indicate that elaborate subliminal processing does occur with little help of top-down attention.

Nevertheless, evidence for elaborate subliminal processing is limited, and effect sizes of masked priming are often small and difficult to be replicated (Van den Bussche, Van den Noortgate, & Reynvoet, 2009). One reason for the paucity of reliability in masked priming is the way that priming effects have been measured: response time and performance accuracy have been staples for behavioral measures of masked semantic priming. However, these measures provide only two data points in each trial. Response times are not very informative in this regard because they reduce dynamic cognitive processes unfolding within a brief duration of priming into a single data point (Spivey & Dale, 2006); performance accuracy, which is represented by a binary value of 0 or 1, is hard to interpret for individual trials.

Recent studies show that the method that tracks trajectories of the computer cursor during decision-making provides viable information about subliminal semantic priming (Dale, Kehoe, & Spivey, 2007; Yamauchi, Kohn, & Yu, 2007). In each trial, participants use the computer mouse to make a response (reaching a target button and click the button to indicate a response). When participants are conducting this choice reaching task, the cursor position on the screen is recorded every 10-20ms to capture the trajectory of cursor motion (Xiao & Yamauchi, 2014, 2015; Yamauchi, 2013; Yamauchi & Bowman, 2014; Yamauchi, Kohn, & Yu, 2007; Yamauchi et al., 2015). Conventional response time records the duration from the onset of a target stimulus to the end of a key press. In-between no concrete information can be gleaned in this measure. However, the cursor motion method records real-time temporal-spatial information underlying participants' dynamic decision-making processes (Freeman & Ambady, 2010; Freeman & Ambady, 2011). By examining real-time features of decision-making, temporal-spatial data provide insights into elaborate subliminal processing (McKinstry, Dale, & Spivey, 2008; Song & Nakayama, 2009; Spivey & Dale, 2006).

Earlier studies demonstrated that hand motion in choice-reaching tasks reflects participants' unconscious judgment and decision-making processes (Aglioti, DeSouza, & Goodale, 1995; Milner & Goodale, 1995). Recently, a number of studies have applied cursor motion measures to study subliminal semantic judgment. For example, perceptual and semantic priming can be distinguished by different cursor trajectory patterns (Finkbeiner & Friedman, 2011; Friedman & Finkbeiner, 2010). Congruency effects can be reliably measured by attractions toward unintended choices of cursor trajectories (Xiao & Yamauchi, 2014).

Moreover, a growing number of studies have demonstrated the advantage of the cursor motion measure over the traditional reaction time measure (Boulenger, Roy, Paulignan, Deprez, & Jeannerod, 2006; Chapman et al., 2010; Faulkenberry, 2014; Faulkenberry & Rey, 2014; Santens, Goossens, & Verguts, 2011; Spivey, Grosjean, & Knoblich, 2005). This advantage is pronounced particularly in subliminal processing (Freeman, Johnson, Ambady, & Rule, 2010; Freeman, Pauker, Apfelbaum, & Ambady, 2010). A recent study comparing the cursor motion measure and response time measure also indicates that the effect size for priming obtained from the cursor motion measure is significantly larger than that by response times (Xiao, Yamauchi, & Bowman, 2015).

In summary, the absence of semantic priming without assistance from cognitive control reported previously can be attributed to the lack of sensitivity with response time measures. Combining dynamic measures of cursor motion with masked priming procedures serves as a powerful tool to uncover mechanisms of semantic priming. On this basis, I employ the cursor motion method to clarify the relationship between elaborate subliminal processing and cognitive control through five experiments.

CHAPTER II

MEASURE MASKED SEMANTIC PRIMING WITH CURSOR MOTION*

2.1 Overview of Experiments 1 & 2

The goal of Experiments 1 and 2 was to develop a viable cursor motion method for masked semantic priming. Although many studies support the idea of *elaborate* subliminal processing, masked priming effects are often small and difficult to replicate (Bussche, Noortgate, & Reynvoet, 2009). Some masked priming studies are based on small sample size (e.g., 10-20 participants), or do not have a rigorous awareness test (Desender & Van den Bussche, 2012). Furthermore, the prime-target relation in these studies is often straightforward, undermining the argument for semantic priming because the perceptual similarity between primes and targets could be the source of priming. For example, in the Opstal et al. study (Opstal, Gevers, Osman, & Verguts, 2010), participants judged whether two numbers were the same or different (e.g., “3 and 5” or “3 and 3”), preceded by two masked priming letters (e.g., “A and a” or “A and g”). In this study, the identical judgment requirement (same / different) applied to both the target number pairs and the priming letter pairs; thus, a learned stimulus-response mapping could facilitate the processing of masked primes. As a result, their congruency effects might have been exaggerated by the direct prime-target link. Research shows that

---

*Part of this chapter is reprinted with permission from “Semantic priming revealed by mouse movement trajectories.” by Xiao, K., & Yamauchi, T., 2014. *Consciousness and Cognition*, *27*, 42-52, Copyright [2014] by Elsevier Inc.

congruency effects are particularly robust when the prime-target relatedness is high (Ortells, Marí-Beffa, & Plaza-Ayllón, 2012).

To partially mitigate this mapping problem, a cursor motion measure rather than the response time measure was employed. The merit of the cursor motion method is that it records dynamic temporal-spatial information about participants' responses (Freeman & Ambady, 2010). Evidence suggests that hand movement reveals unconscious cognition: participants automatically adjusted their fingers when pointing to a target without awareness (Aglioti, DeSouza, & Goodale, 1995; Song & Nakayama, 2009). By analyzing temporal-spatial features of cursor motion trajectories, insights can be gained to understand subliminal processing. Recent studies found that perceptual priming and semantic priming could be distinguished by different cursor trajectory patterns (Friedman & Finkbeiner, 2010); cursor motion trajectories were constantly attracted to unselected options before clicking the intended option in incongruent trials due to semantic conflicts (Freeman, Ambady, Rule, & Johnson, 2008). The magnitude of attraction is measured by the area under the curve (AUC), which is calculated as the geometric area circumscribed by the straight line from the onset position to the ending position and the actual trajectory that veers toward the unselected option. In the current experiment, participants judge whether two numbers are the same or different by clicking one of the two buttons (i.e., "Same" or "Different") on the top of the computer screen (Figure 1).

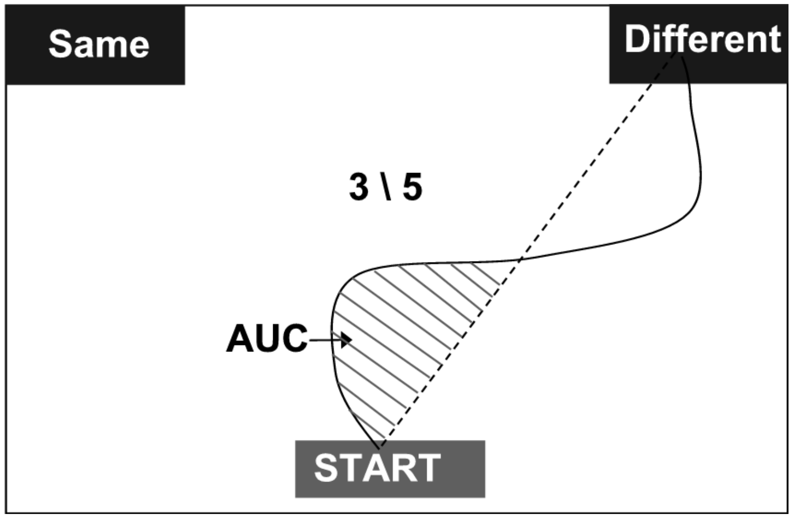


Figure 1. Illustration of the area under the curve (AUC). The curve represents a hypothetical trajectory of a cursor from the onset position (“START” button) to the ending position (clicking the “Different” button). The straight line represents the “ideal path” between the onset and ending position. The AUC is the area circumscribed by the ideal path and the actual trajectory curve that exceeds the ideal path toward the unselected option (shaded area) and is measured by the amount of pixels.

To make the relation between primes and targets indirect, I replace letter primes (e.g., “A a”) with symbolic pictures with either positive (e.g., “go”) or negative (e.g., “no go”) connotations but still use the number pairs as targets (Figure 2). Participants make same / different judgments for number pairs (e.g., “3 \ 5”), whereas the priming pictures are not directly linked to semantic meanings as “same” or “different.” It is expected that when responding to incongruent trials (e.g., positive primes followed by 3 \ 5 or 5 \ 3, or negative primes followed by 3 \ 3 or 5 \ 5), the cursor trajectories should move towards the unselected option, as compared to congruent trials, resulting in larger AUC in incongruent trials than in congruent trials.

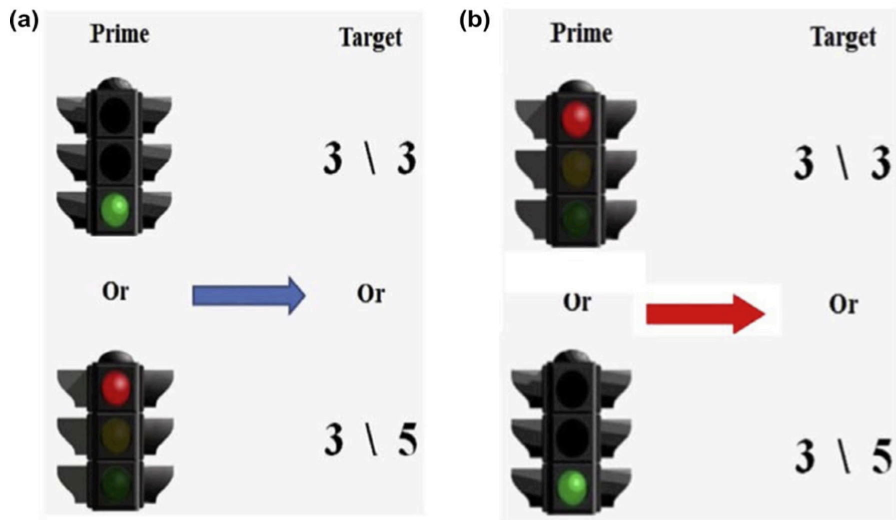


Figure 2. Illustrations of congruent and incongruent trials in Experiment 1. Participants judged whether the target numbers were the same or not, preceded by a briefly presented picture with either positive (e.g., a green light) or negative (e.g., a red light) connotations. For example, trials where the prime was a green light and the target was ‘‘3 \ 3’’ (or the prime was a red light and the target was ‘‘3 \ 5’’) were considered as congruent trials. These prime-target relationships were swapped in incongruent trials.

In psychophysics studies involving perceptual learning (Schoups, Vogels, & Orban, 1995), the same / different judgments of stimuli are known to correspond to “yes” or “no” responses, respectively. It is also known that positive (“yes”) responses take shorter reaction time than negative (“no”) responses (Sternberg, 1966). A similar trend is present in the “same / different” judgment task: “same” responses result in shorter RT than “different” responses (Ratcliff, 1985; 1987). According to the Unified Theory (Proctor, 1981), such reaction time differences indicate that “same” and positive (“yes”) judgments employ an analogous processing mechanism, as distinct from the process underlying “different” or negative (“no”) judgments. Following this reasoning, I assume that priming pictures with positive connotations (e.g., a green traffic light) are congruent with “same” responses (e.g., “3 \ 3”) while primes with negative connotations (e.g., a red traffic light) correspond to “different” responses (e.g., “3 \ 5”). Accordingly, I predict that positive primes (e.g., a green traffic light) facilitate “same” responses, and negative primes facilitate “different” responses; in contrast, negative primes impede “same” responses, and positive primes impede “different” responses (Figure 2).

Translating this prime-target relationship into cursor motion trajectories, larger AUCs should be observed for incongruent trials than congruent trials. If such an indirect semantic link between primes and targets still yields significant priming effects, it adds further evidence to the notion of *elaborate* subliminal processing.

2.2 Experiment 1

Experiment 1 consisted of two phases: a numeric judgment phase and an awareness test phase, which was given in sequence. In the numeric judgment task, participants judged whether two numbers were same or different, preceded by a briefly presented picture (Figure 3a). The trials in the awareness test phase were identical to those in the number judgment task, but participants were explicitly instructed to identify the prime and choose the correct prime from two options (Figure 3b).

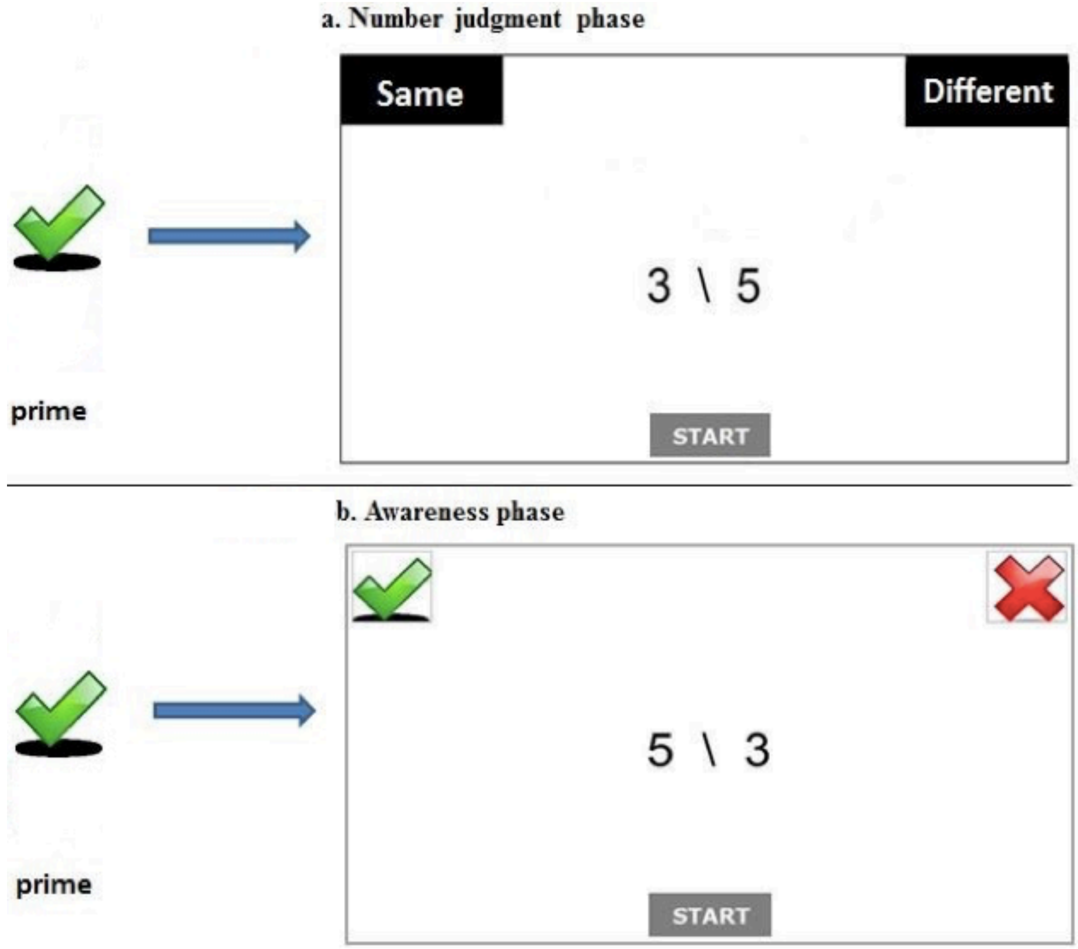


Figure 3. Illustrations of the number judgment task and the awareness test. In (a) the number judgment task, participants judged if two numbers were the same or different preceded by a briefly presented prime (e.g., a check). In (b) the awareness test, participants were asked to identify the preceding prime and click the correct picture in the two options.

2.2.1 Participants

A total of 382 undergraduate students from Texas A&M University participated in this experiment for course credits. They were randomly assigned to four conditions of prime duration. Eight participants did not complete the experiment. Additional seven participants were excluded from data analysis because their response accuracy was below 90%. Thus, the data from 367 participants were analyzed (n = 88 in the 20ms duration condition; n = 96 in the 50ms duration condition; n = 91 in the 100ms duration condition; and n = 92 in the 150ms duration condition).

2.2.2 Materials

Prime stimuli were three pairs of symbolic pictures (Figure 4). Each pair consisted of one with positive connotations and the other with negative connotations. Four number pairs were used as target stimuli; two of them required “same” responses (i.e., “3 \ 3” or “5 \ 5”), and the other two required “different” responses (i.e., “3 \ 5” or “5 \ 3”).

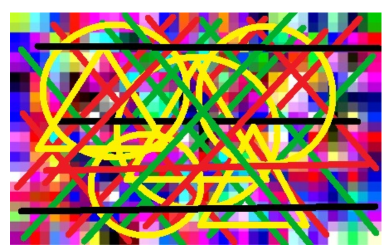
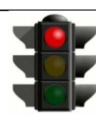
Pair No.	Prime type		Mask
	Positive	Negative	
Pair 1			
Pair 2			
Pair 3			

Figure 4. Pictures used as primes and masks in this experiment. Each picture is associated with either positive or negative connotations.

2.2.3 Apparatus and procedure

An 180 Hz monitor was used to present the stimuli. In each trial, a fixation cross was presented at the center of the screen for 300ms. Then, a pre-mask was presented for 100ms, followed by a priming picture, then a post-mask for 100ms. Finally, the target was presented until participants responded. The primes (Figure 4) were presented for 20ms, 50ms, 100ms, or 150ms, depending on the prime duration condition to which participants were assigned (between-subjects conditions). The experiment was controlled by the Mouse Tracker software developed by Freeman and Ambady (2010).

The participants were instructed to judge whether the two numbers were the same or different, using a mouse to click the "Same" or "Different" button on the top of the screen quickly and accurately while ignoring any pictures flashed prior to the numbers.

In the cursor motion analysis, the response time measure was defined as the duration of time from the onset of a target until participants clicked the "Same" or "Different" button. The AUC of a cursor motion trajectory in each trial was the geometric area between a straight line from the onset position to the ending position and the actual trajectory exceeding the straight line toward the unselected option (Figure 5). Smaller AUCs indicate that the trials are easier to respond to, while larger AUCs more difficult (Freeman & Ambady, 2010). To draw the trajectory, the position of the cursor on the screen (i.e., measured by x-y coordinates) is recorded as one data point every 13-16ms; then all the data points are normalized into 100 steps for each trial using a linear interpolation method.

(a) (b)

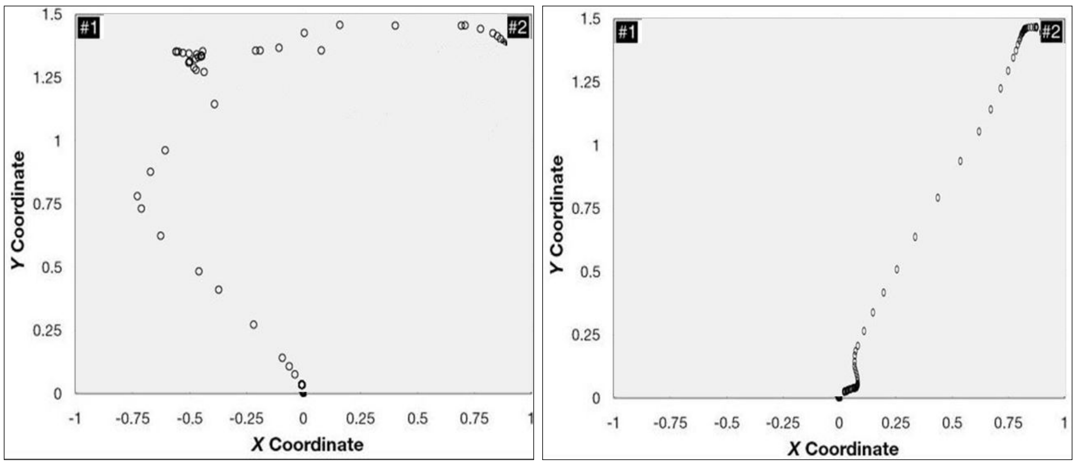


Figure 5. Two real examples of cursor trajectories. There Figure 5a shows a trajectory with a large attraction towards the unselected option (large AUC), and Figure 5b shows a trajectory with a small AUC. The X coordinate is scaled by normalizing the total amount of pixels in a row as 2 units, while the Y coordinate is scaled by normalizing the total amount of pixels in a line as 1.5 units. Therefore, the total amount of pixels on the screen is normalized as 3 units.

After the number judgment phase, participants carried out an awareness test. The trials in the awareness test were identical to those in the number judgment task. However, participants were informed of the prime and asked to identify it by clicking one of the two options. There were 96 trials in the awareness test. The *d'* measure obtained from the awareness test was applied to examine the extent to which the visibility of the primes influenced the magnitude of the priming effects. Specifically, selecting the option that was presented as a prime was regarded as "hit" and incorrectly selecting the same option that was not actually presented was regarded as 'false alarm'. (Macmillan & Creelman, 1996).

2.2.4 Design

The experiment was conducted with a 4 (prime duration: 20ms, 50ms, 100ms, 150ms; between-subjects) × 2 (prime type: positive, negative; within-subjects) × 2 (target type: same, different; within-subjects) design. For actual data analysis, I applied two sets of ANOVA. In one set, I collapsed prime type and target type as one factor of congruency (congruent, incongruent) and employed 4 (prime duration: 20ms, 50ms, 100ms, 150ms; between-subjects) × 2 (congruency: congruent, incongruent; within-subjects) ANOVA. In the other set, I applied two 4 (prime duration: 20ms, 50ms, 100ms, 150ms; between-subjects) × 2 (congruency: congruent, incongruent; within-subjects) ANOVAs separately for the trials that required "same" responses and "different" responses.

Number pairs consisting of same numbers were called positive targets (e.g., "3 \ 3"), and pairs of different numbers were called negative targets (e.g., "3 \ 5"). Before the target, a masked picture with either positive or negative connotations was briefly presented as the prime, which was respectively called the positive or negative prime. Trials that contained a positive prime and a positive target were called PP trials; Trials that contained a negative prime and a negative target were called NN trials; Trials that contained a positive prime and a negative target were called PN trials; Trials that contained a negative prime and a positive target were called NP trials. PP and NN trials were classified as congruent trials while PN and NP trials as incongruent trials. There were 240 trials for each participant (120 congruent trials and 120 incongruent trials). These trials were further divided into two categories requiring either “same” or “different” responses (Table 1). The order of presenting trials was randomly determined, and whether the “Same” button was on the left or right side of the screen was fixed for each participant whereas randomly determined between participants.

Table 1 Number of trials in each condition

Congruency	Combination	Prime	Target	Number of Trials
congruent trials (120)	PP (60)	positive primes	3 \ 3	30
		positive primes	5 \ 5	30
	NN (60)	negative primes	3 \ 5	30
		negative primes	5 \ 3	30
incongruent trials (120)	NP (60)	negative primes	3 \ 3	30
		negative primes	5 \ 5	30
	PN (60)	positive primes	3 \ 5	30
		positive primes	5 \ 3	30

2.2.5 AUC results

Based on the findings that positive judgment is faster than negative judgment and positive (i.e., “same”) / negative (i.e., “different”) number judgments are carried out by distinct cognitive processes (Proctor, 1981), I analyzed congruency effects with both overall data (i.e., collapsing “same” and “different” judgment trials) and data separating “same” judgment trials and “different” judgment trials.

I focused on the cursor motion measure AUC, which is measured by the amount of pixels. In actual data analysis, the total amount of pixels in each *row* was scaled by the X-coordinate ranging from -1 to 1 (i.e., 2 units of pixels in total on the X-coordinate), and the total amount of pixels in each *line* was scaled by the Y-coordinate ranging from 0 to 1.5 (i.e., 1.5 units of pixels in total on the Y-coordinate). Therefore, the total amount of pixels on the screen is normalized as 3 units (i.e., 1.5×2).

A summary of overall congruency effects is described first, and congruency effects analyzed separately for positive response trials (i.e., trials required "same" responses) and negative response trials (i.e., trials required "different" responses) are introduced next. Following this analysis, I report the extent to which the visibility of primes influenced the congruency effects using regression analyses. The response time analysis is reported as the complementary data at the end.

The cursor motion data shows significant congruency effects. Overall, the AUCs in incongruent trials was larger ($M = 0.73$, $SD = 0.39$) than those in congruent trials ($M = 0.67$, $SD = 0.35$); $F(1, 366) = 54.76$, $MSE = 0.61$, $p < 0.001$, partial $\eta^2 = 0.13$. Such congruency effects were substantial in all durations (Table 2); t's > 3.30, p's < 0.002. There was no interaction between prime duration and congruency; $F < 1.00$, suggesting that the duration of prime did not affect the congruency effects. Note that this absence of interaction was not due to a lack of statistical power, given that the data was from a large sample. A power analysis showed that the probability of falsely accepting a null hypothesis (type II error) was only 0.04.

Table 2 Comparisons of AUCs between congruent and incongruent trials

duration	*N*	Incongruent	Congruent	*t*	*p*	Cohen's *d*
20ms	88	0.75	0.70	3.47	0.001	0.74
50ms	96	0.69	0.63	4.92	<0.001	1.01
100ms	91	0.77	0.71	3.34	0.001	0.70
150ms	92	0.70	0.64	3.39	0.001	0.71
overall	367	0.73	0.67	7.45	<0.001	0.78

Note. The total amount of pixels on the screen is normalized as 3 units, and the AUC measured by the amount of pixels is normalized proportionally.

The congruency effects were significant for both positive and negative response trials, and the effect size appeared larger in positive response trials (Table 3), though the interaction between response type (i.e., positive response trials and negative response trials) and congruency was not significant; $F(1, 366) = 1.08$, $MSE = 0.02$, $p > 0.30$, partial $\eta^2 < 0.01$. For positive response trials, robust congruency effects were found in all four durations (Table 3); while for negative response trials, congruency effects were weaker (Table 4). In addition, there was no interaction between duration and congruency, neither in positive nor negative response trials; $F < 1.00$.

Table 3 Comparisons of AUCs for positive response trials

duration	*N*	Incongruent	Congruent	*t*	*p*	Cohen's *d*
20ms	88	0.75	0.68	3.81	<0.001	0.82

Table 3 Continued

duration	*N*	Incongruent	Congruent	*t*	*p*	Cohen's *d*
100ms	91	0.74	0.66	3.78	<0.001	0.80
150ms	92	0.71	0.64	3.64	<0.001	0.76
overall	367	0.71	0.64	6.37	<0.001	0.67

Note. The total amount of pixels on the screen is normalized as 3 units, and the AUC measured by pixels is normalized proportionally.

Table 4 Comparisons of AUCs for negative response trials.

duration	*N*	Incongruent	Congruent	*t*	*p*	Cohen's *d*
20ms	88	0.74	0.71	1.58	0.119	0.34
50ms	96	0.70	0.64	2.99	0.004	0.61
100ms	91	0.79	0.76	1.34	0.182	0.28
150ms	92	0.67	0.63	1.82	0.074	0.38
overall	367	0.74	0.69	4.61	<0.001	0.48

Note. The total amount of pixels on the screen is normalized as 3 units, and the AUC measured by pixels is normalized proportionally.

To investigate the influence of prime visibility on congruency effects, *d'* was calculated to assess the extent to which participants could identify primes (Greenwald, Draine, & Abrams, 1996). Specifically, correctly choosing a positive prime was regarded as "hit," while incorrectly choosing the positive prime was regarded as "false alarm." For participants with perfect detection performance (i.e., 100% accuracy in the awareness test), *d'* was calculated by 99% "hit" rate and 1% "false alarm" rate (Stanislaw & Todorov, 1999). T-tests showed that *d'*s were significantly above zero in all four prime durations, indicating that many participants could identify primes. As expected, the longer the prime duration was, the higher the *d'* was (Table 5).

Table 5 Descriptive statistics of *d*'s and t-tests in the awareness test

duration	*N*	*M*	*Mdn*	*SD*	*t*	*p*
20ms	88	0.55	0.54	0.47	7.76	<0.001
50ms	96	1.56	1.68	1.00	10.81	<0.001
100ms	91	2.25	2.88	1.09	13.92	<0.001
150ms	92	2.52	3.00	0.86	19.87	<0.001

Note. The t-tests were performed by comparing *d'*s with zero.

Regression analyses were performed on *d'* as the predictor with the priming magnitude as the predicted variable. The priming magnitude was calculated by subtracting AUCs in congruent trials from those in incongruent trials. A significant intercept of the regression line at null *d'* indicates a significant priming effect when participants can hardly identify masked primes (Greenwald, Draine, & Abrams, 1996). In addition, if the slope of the regression line is not different from zero, it suggests that the priming effect is relatively independent of the awareness of the primes (Desender & Van den Bussche, 2012). Overall, the regression on *d'* revealed a significant intercept ($b_0 = 0.05$, $t = 3.77$, $p < 0.001$), and the slope of the regression line was not different from zero ($b_0 = 0.003$, $t = 0.46$, $p > 0.64$), implying that the visibility of primes had little influence on the congruency effects.

Finally, to examine whether the priming effects were influenced by response type (i.e., "Same" or "Different") or by location of the "Same" and "Different" buttons (e.g., "Same" button on the left or right side of the screen), a four-way ANOVA, prime duration (20, 50, 100, 150ms) × congruency (congruent, incongruent) × response type (same, different) × button location (left, right), was performed. This analysis showed that the congruency factor did not interact with any other factors, $F < 1.00$.

Regression analyses were also performed in each prime duration condition, respectively for positive and negative response trials. For positive response trials, intercepts were significantly above zero in 20ms, 50ms, and 100ms duration conditions; for negative response trials, the intercept was significant only in the 50ms duration condition (Table 6; Figure 6). This suggests that the size of priming effects depended on positive / negative responses, and was larger for positive response trials.

Table 6 Regressions with AUCs on *d*'s in each duration

Duration	Response	Predictor	*B*	*t*	*p*
20ms	Positive	Constant	0.067	2.332	0.022
		d'	0.005	0.130	0.897
	Negative	Constant	-0.004	-0.108	0.914
		d'	0.069	1.485	0.141
50ms	Positive	Constant	0.080	2.500	0.014
		d'	0.045	0.983	0.934

Table 6 Continued

Duration	Response	Predictor	*B*	*t*	*p*
	Negative	Constant	0.003	2.139	0.035
		d'	0.013	0.661	0.510
100ms	Positive	Constant	0.114	2.282	0.025
		d'	-0.014	-0.704	0.483
	Negative	Constant	-0.038	-0.681	0.498
		d'	0.002	0.110	0.913
150ms	Positive	Constant	0.080	1.117	0.267
		d'	-0.015	-0.568	0.571
	Negative	Constant	0.050	0.791	0.431
		d'	0.009	0.366	0.716

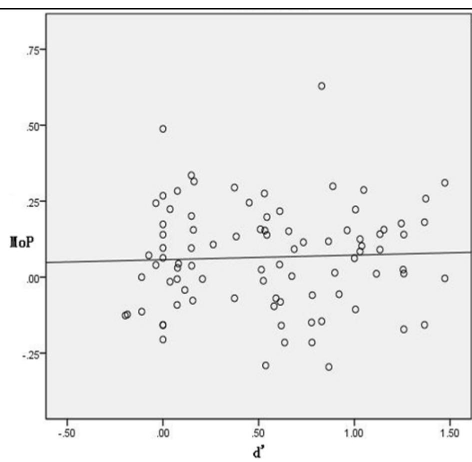
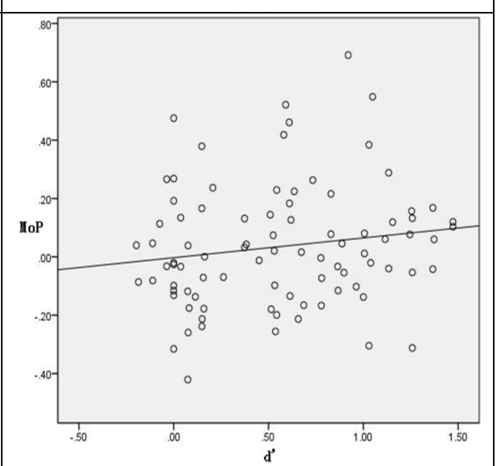
Duration	Positive Response	Negative Response
20ms		

Figure 6. Regressions with priming magnitudes on *d'*s in each duration. The x-axis represents *d'* and the y-axis represents the magnitude of priming (MoP). An accuracy of 100% is regarded as 99% hit and 1% false alarm (Stanislaw & Todorov, 1999).

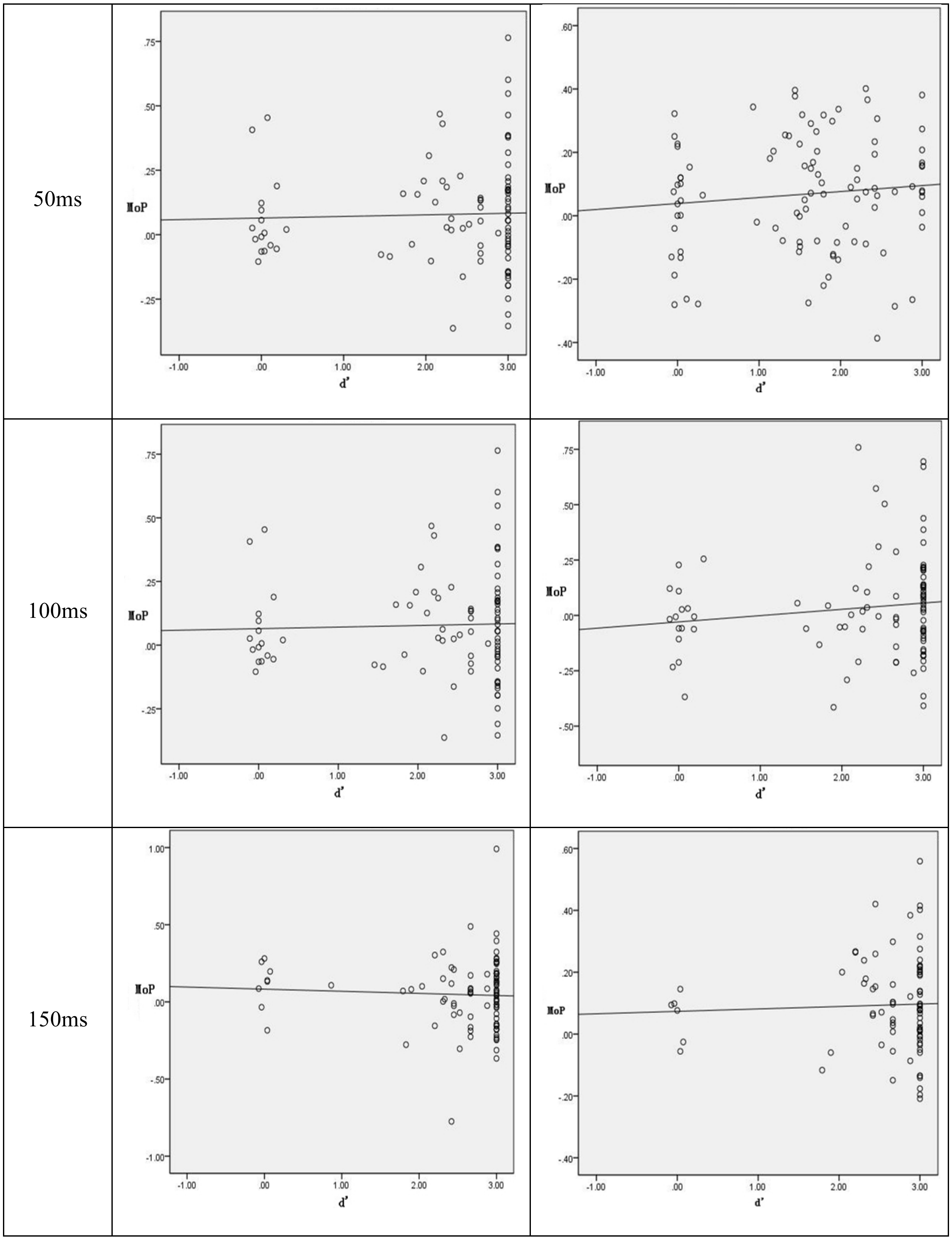


Figure 6 Continued.

To summarize, the AUC revealed consistent congruency effects in all four durations (Table 2). Congruency effects seemed larger for positive response trials, as compared to negative response trials (Tables 3 & 4). The *d'*s in the awareness test were quite high (Table 5), and further regression analyses showed that the intercepts were significantly higher than zero in the 20ms, 50ms, and 100ms prime duration for positive response trials (Table 6).

2.2.6 Response time analysis

Compared with the cursor motion data, the overall congruency effects measured by response times were weaker; the mean RT in incongruent trials was significantly longer (M =1107.68, SD = 109.85) than that in congruent trials (M = 1103.91, SD = 110.19); $F(1, 363) = 4.94$, $MSE = 2502.87$, $p = 0.03$, partial $\eta^2 = 0.01$. There was no interaction effect between prime duration and congruency; $F<1.0$. This suggests that the visibility of primes did not influence the magnitude of priming.

T-tests applied to each duration showed that the mean response times were significantly shorter in congruent trials than in incongruent trials in the 50ms duration condition: $t(95) = 2.06$, pooled $SD = 29.55$, $p = 0.04$, $d = 0.42$, 95% CI_d [0.13, 0.71]. A similar trend was present for the remaining three conditions except for the 20ms group, where the average RTs in congruent and incongruent trials were nearly identical (Table 7).

Table 7 Response times for congruent and incongruent trials

duration	*N*	Incongruent	Congruent	*t*	*p*	Cohen's *d*
20ms	88	1077.11	1077.40	0.10	0.92	0.02
50ms	96	1118.65	1112.49	2.04	0.04	0.42
100ms	91	1103.95	1100.54	0.93	0.36	0.20
150ms	92	1129.15	1123.67	1.51	0.14	0.32
Together	367	1107.68	1103.91	2.27	0.02	0.24

Congruency effects were found for positive response trials (Table 8), but not for negative response trials (Table 9). The interaction between response type and congruency was significant; $F(1, 366) = 6.40$, $MSE = 937.82$, $p = 0.01$, partial $\eta^2 = 0.02$. There was no interaction between prime duration and congruency, neither for positive nor negative response trials; $F < 1.00$.

Table 8 Comparisons of response times for positive response trials

duration	*N*	Incongruent	Congruent	*t*	*p*	Cohen's *d*
20ms	88	1075.97	1072.60	0.80	0.43	0.17
50ms	96	1108.20	1101.63	1.56	0.12	0.32
100ms	91	1098.04	1086.62	2.44	0.02	0.51
150ms	92	1122.73	1112.95	2.14	0.04	0.45
overall	367	1101.60	1093.79	3.53	<0.001	0.37

Table 9 Comparisons of response times for negative response trials

duration	*N*	Incongruent	Congruent	*t*	*p*	Cohen's *d*
20ms	88	1078.26	1082.20	-0.92	0.36	0.20
50ms	96	1129.10	1123.34	1.28	0.20	0.26
100ms	91	1109.86	1114.45	-0.90	0.37	0.19
150ms	92	1135.57	1134.39	0.23	0.82	0.05
overall	367	1113.76	1114.04	-0.12	0.91	0.01

A regression analysis showed that the intercept was not different from zero; $b_0 = 1.02$, $t = 0.34$, $p > 0.73$. The slope was not different from zero; $b_0 = 1.59$, $t = 1.12$, $p > 0.26$. In addition, prime duration did not interact with congruency effects, $F < 1.00$. Further regression analyses performed separately for positive and negative response trials in each duration showed intercepts above zero in the 100ms condition (Table 10).

Admittedly, the cursor motion method does not record the response time in a conventional way, because the conventional response time is the duration from the onset of a target stimulus till participants pressing a response button. For the same task, the response time recorded by cursor motion may be longer than the conventional response time. Nevertheless, these findings are consistent with the idea that the magnitude of priming was subject to response types, and larger priming effects were found for positive response trials.

Table 10 Regressions with priming magnitudes on *d*'s

Prime Duration	Response	Predictor	*B*	*t*	*p*
20ms	Positive	Constant	4.952	0.752	0.454
		d'	-2.864	-0.315	0.754
	Negative	Constant	-6.089	-0.912	0.364
		d'	3.895	0.422	0.674
50ms	Positive	Constant	4.789	0.610	0.543
		d'	1.140	0.269	0.789
	Negative	Constant	5.620	0.672	0.503
		d'	0.089	0.020	0.984
100ms	Positive	Constant	21.537	2.003	0.048
		d'	-4.507	-1.046	0.299
	Negative	Constant	24.671	2.148	0.034
		d'	8.945	1.943	0.055
150ms	Positive	Constant	24.857	1.748	0.084
		d'	-5.973	-1.119	0.266
	Negative	Constant	-13.345	-0.828	0.410
		d'	5.758	0.952	0.343

2.2.7 Discussion

In Experiment 1, I adopted the "same / different" judgment task from the Van Opstal et al., (2010) study, and replaced their letter-pair primes (e.g., "A, a") with "positive / negative" pictures to make the prime-target relation indirect. The AUCs for congruent trials were smaller than those for congruent trials, indicating that the positive or negative connotations of primes influenced the "same / different" judgment on numbers. Furthermore, the coefficients in the regression analysis were nearly zero, suggesting that the awareness of primes had little influence on priming. Overall, the congruency effects were larger for positive response trials than negative response trials, and larger for the AUC data than the response time data.

Was the semantic processing of primes subliminal? The awareness test indicates that primes were visible to many participants. On the other hand, there was no correlation between priming magnitudes and *d'*s, and there were significant intercepts at null *d'*. Thus, it was possible that for participants who could hardly identify the primes, semantic priming still occurred. However, given the high visibility of primes, regression analysis showing significant priming at null *d'* does not guarantee that the semantic priming was subliminal.

One reason for participants' high awareness of primes was that I did not employ a standard awareness test, where participants were asked to perform the same semantic judgment on primes as they responded to targets (Greenwald et al., 1996). Unfortunately, this was impossible in my experiment, because the "same / judgment" task could not be applied to single pictures. As a result, a perceptual detection task was applied in the awareness test, and many participants could select the correct priming pictures simply based on perceptual features such as colors and contours.

To reduce the stimulus-response mapping, I made the link between primes and targets indirect; the "same / different" judgment on numbers could hardly be applied to a single picture such as a red light. Primes and targets were only weakly associated via their positive or negative connotations. Such weak prime-target associations still elicited salient priming.

The results of RTs were roughly consistent with those of AUCs, and larger congruency effects were found for AUCs than RTs. Although my cursor motion method did not record standard RTs in a traditional way (i.e., pressing a response keyboard rather than clicking a mouse), it can be inferred that the AUC may be more sensitive to masked semantic priming.

In summary, masked pictures influenced numeric judgment even though the prime-target relation was indirect, adding further evidence to the notion of *elaborate* masked priming. The priming was not influenced by the visibility or duration of primes. Overall, the analysis of this large sample of data demonstrates that AUC can reliably measure masked semantic priming. Experiment 2 compared directly the effect size of the AUC measure and the standard response time measure.

2.3 Experiment 2

To directly compare the AUC and RT measures, two independent experiments applying the cursor motion measure and response time measure were conducted. A different group of participants was recruited for each experiment, and participants performed the same number judgment tasks as described in Experiment 1 (Xiao & Yamauchi, 2014). Both experiments consisted of two phases: a number judgment task followed by an awareness test. In the number judgment task, participants judged whether two numbers were the same or different, preceded by a briefly presented picture (i.e., prime). The trials in the awareness test were identical to those in the number judgment task except that participants were explicitly instructed to identify the primes and choose the correct prime from two options.

2.3.1 Participants

In total, 64 undergraduate students from Texas A&M University participated in this study for course credits. Among them, 28 participants were assigned to the cursor motion condition, while 36 to the response time condition.

2.3.2 Procedures

Stimuli and procedures were the same as in Experiment 1, except for minor modifications. In the cursor motion condition, participants were instructed to use a computer mouse to click the “Same” or “Different” button on the top of the screen quickly and accurately. In the response time condition, participants were instructed to press the “F” button on a keyboard to choose “Same” and the “J” button to choose “Different.” The prime duration was fixed at 20ms in both conditions. The left / right locations of the “Same” and “Different” buttons in the cursor motion condition were counterbalanced between participants.

2.3.3 Results

Trials with a response time longer than 3000ms were dropped (less than 2% of the entire trials). Paired t-tests were performed to assess congruency effects. For the cursor motion experiment, the AUC was smaller in congruent trials (M = 3628.43, SD = 3875.79) than in incongruent trials (M = 4746.17, SD = 4135.95), $t(27) = 5.13$, $p < 0.001$, $d = 1.97$, 95% CI_d [1.31, 2.64] (Rosnow & Rosenthal, 1991; Fritz, Morris, & Richler, 2012). Similarly, for the response time experiment, the response time (RT) was also shorter in congruent trials (M = 733.32, SD = 156.28) than in incongruent trials (M = 759.50, SD = 168.60). However, this difference was only marginally significant; $t(35)$ = 1.92, p = 0.06, d = 0.65, 95% CI_d [0.16, 1.14].

To compare the magnitude of the congruency effects obtained in the cursor motion condition and in the response time condition, I contrasted the p values and effect sizes between the two conditions with a meta-analytic method. For this analysis, Z is determined by the formula $Z = (Z_1 — Z_2)/\sqrt{(2)}$, where Z_1 represents Z-value obtained from the p-value in one condition (e.g., the cursor motion condition) and Z_2 represents Z-value obtained from the p-value in the other condition (e.g., the response time condition) (Rosenthal, 1991). This analysis showed that the p-value obtained in the cursor motion condition was significantly smaller than that in the response time condition; Z = 2.56, p = 0.005 (one-tailed). To compare effect sizes, Z is determined by the formula $Z = (Z_{r1} — Z_{r2})/\sqrt{(1/(N_1\text{-}3)+1/(N_2\text{-}3))}$; Z_{r1} represents Z-value obtained from the effect size in the cursor motion condition, and Z_{r2} represents Z-value obtained from the effect size in the response time condition; N_1 and N_2 represents number of participants respectively in these two conditions (Alexander, Scozzaro, & Borodkin, 1989; Snedecor & Cochran, 1989). This analysis showed that the effect size obtained in the cursor motion condition was significantly larger than that in the response time condition; Z = 2.08, p = 0.018 (one-tailed).

To examine whether priming occurred at a subliminal level, I calculated the *d'*s in the awareness test to measure the extent to which participants could identify the masked primes (Greenwald, Draine, & Abrams, 1996). The *d'*s were significantly above zero in the AUC group (*M* = 0.29, *SD* = 0.33, $t(27) = 9.71$, $p < 0.001$) and the RT group (*M* = 0.40, *SD* = 0.47, $t(35) = 9.05$, $p < 0.001$). To assess whether the priming effects depended on the visibility of primes, I performed a linear regression analysis with priming magnitudes (i.e., $AUC_{incongruent} — AUC_{congruent}$) on *d'*s (Greenwald et al., 1996; Van Opstal, Gevers, Osman, & Verguts, 2010).

For the AUC data, there was no correlation between priming magnitudes and *d'*s, $b^* = 0.29$, $t(26) = 1.55$, $p = 0.14$, suggesting that the congruency effect was not influenced by prime visibility. There was a significant intercept at null *d'*; $b_0 = 758.16$, $t(26) = 2.40$, $p = 0.02$, indicating that the congruency effect was still significant for participants who could hardly see the primes.

The same regression analysis was performed for RT data. A linear regression on *d'* with the priming magnitude as the predicted variable revealed no correlation between the priming magnitudes and *d'*s, $b^* = -0.057$, $t(34) = -0.33$, $p = 0.74$; the congruency effect was not influenced by prime visibility, and the intercept was not significant at null *d'*; $b_0 = 30.60$, $t(34) = 1.59$, $p = 0.12$.

2.3.4 Discussion

Both AUC and RT data showed congruency effects. Moreover, the effect size of congruency effects measured by AUCs was significantly larger than that by RTs. Similarly, the *p*-value of the congruency effect measured by AUCs was significantly smaller than that by RTs. At least two factors are likely to contribute to this disparity.

First, response times record only the duration from the onset of a target until a response is made, but no information is recorded in-between. Such information is essential to understand masked semantic priming, as semantic decision-making is likely to unfold dynamically and a prime influences a target continuously rather than discretely (Son & Nakayama, 2007). In contrast, the AUC integrates temporal-spatial information in real-time cognition; thus, the AUC is likely to capture dynamic decision-making processes.

Second, response time data is often influenced by the Gratton Effect — participants more or less estimate their response times and try to control it, which results in reduced congruency effects due to participants' effort to resist the impact of priming (Gratton, Coles, & Donchin, 1992). The cursor motion data is beneficial because it combines spatial and temporal information. Temporal data alone is vulnerable to the Gratton Effect, but by combining temporal data and spatial data, the temporal "resistance" can be mitigated.

In summary, both the RT and AUC show congruency effects. However, because the effect size measured by AUCs is far larger than that of RTs, the cursor motion measure seems more sensitive to masked semantic priming. In the next Chapter, Experiments 3-5 apply the cursor motion method developed in Experiment 1 and 2 to investigate the role of top-down attention in subliminal semantic processing.

CHAPTER III

HOW ATTENTION INFLUENCES SUBLIMINAL SEMANTIC PROCESSING*

Applying the cursor motion method, I investigated the influence of top-down attention on subliminal semantic processing in three experiments. In Experiment 3, I employed the number judgment task developed by Naccache et al. (2002) and assessed congruency effects with a cursor motion method. In particular, I examined whether subliminal semantic processing would occur in near absence of attention. Experiment 4 investigated the role of the visual cue (i.e., a green square) and top-down attention using the task developed by the Naccache et al. (2002). Experiment 5 addressed how top-down attention influenced subliminal semantic priming: did top-down attention change the time course of priming or amplify the magnitude of subliminal semantic processing? This question was addressed by manipulating the stimulus-onset asynchrony (SOA) in Experiment 5.

3.1 Experiment 3

In examining the role of top-down attention in subliminal priming, Naccache et al. (2002) instructed participants to judge whether a target digit (e.g., “9”) was larger or smaller than five, preceded by a masked priming digit (e.g., “6”); participants’ top-down attention was manipulated by occasionally presenting a visual cue. The pre-target duration changed randomly from trial to trial, which disrupted participants’ top-down

---

*Part of this chapter is reprinted with permission from “Subliminal semantic priming in near absence of attention: A cursor motion study.” by Xiao, K., & Yamauchi, T., 2015. *Consciousness and Cognition*, *38*, 88-98, Copyright [2015] by Elsevier Inc.

attention because participants could not predict when a target would suddenly appear (i.e., uncued condition). In the cued condition, however, a green square cue was explicitly presented to signal an upcoming target digit to facilitate participants' top-down attention; the interval between the cue and target was fixed. Results show that subliminal congruency effects were present only in the cued condition but not in the uncued condition. On this basis, Naccache et al. (2002) argue that top-down attention is *necessary* for subliminal semantic processing: when participants see the cue and know the target is coming, a temporal attention window is open, amplifying subliminal semantic processing; while in the uncued condition, subliminal primes not covered by the temporal attention window cannot be processed at a semantic level.

However, the absence of priming without attention reported by Naccache et al. (2002) can be attributed to the insufficient sensitivity of response time measures, because the response time is not very informative about dynamic decision-making processes unfolding in real-time. To reveal dynamic semantic decision, I applied the cursor motion method to the experimental task developed by Naccache et al. (2002) and re-examined the congruency effects.

Experiment 3 consisted of two phases, a number judgment task phase, followed by an awareness test phase. In the number judgment task, participants judged whether a target digit (e.g., 7) was larger or smaller than five. Before the presentation of the target digit, a prime digit (e.g., 6) was flashed subliminally for 29ms followed by a mask. As in the Naccache et al. (2002) study, there were two between-subjects conditions — an uncued condition and a cued condition. In the uncued condition, the pre-target duration changed randomly from trail to trial, making it difficult for participants to anticipate when the target would appear. While in the cued condition, a green cue was presented for 200ms to signal the upcoming target, which facilitated participants' top-down attention to stimuli.

In the awareness test, participants received the same set of trials. However, participants were instructed to judge the prime instead of the target (i.e., whether a prime digit was larger or smaller than five).

There are 288 trials in the number judgment task (i.e., 96 cued trials and 192 uncued trials), before which 96 trials were given for practice. In the awareness test, 192 trials were presented.

3.1.1 Participants

A total of 42 undergraduate students from Texas A&M University participated in this experiment for course credits.

3.1.2 Materials and apparatus

Primes and targets were one-digit numbers (i.e., 1, 4, 6, or 9). A 70 Hz monitor was used to present the stimuli. The experimental procedures were controlled by a customized computer program developed with Microsoft Visual Studio.

3.1.3 Procedure

For each trial, a mask (71ms duration) was presented one after another seamlessly in random frequencies ranging from 15 to 25, followed by either a green square cue lasting for 200ms (cued trials) or the same mask for 71ms (uncued trials). Then four masks were presented, followed by a one-digit prime (i.e., 1, 4, 6, or 9) for

29ms. Following that, a 71ms post-mask was presented, then a target digit (i.e., 1, 4, 6, or 9) was shown for 200ms. Participants' task was to judge whether the target digit was larger or smaller than five; they used the mouse to click one of two buttons labeled either "Large" or "Small" on the top right or left corner of the screen. Participants were instructed to response as quickly and accurately as they could. Altogether, there were 96 cued and 192 uncued trials, half of which were congruent and half of which were incongruent (Table 11). For each participant, trials were presented in a random order. Before doing the number judgment task, participants took 96 trials for practice.

Table 11 Numbers of trials in each type of prime-target combinations

Cue	Congruency	Prime	Target	Number of Trials
Cued (96 trials)	congruent	1 or 4	1 or 4	24
		6 or 9	6 or 9	24
	incongruent	1 or 4	6 or 9	24
		6 or 9	1 or 4	24
uncued (192 trials)	congruent	1 or 4	1 or 4	48
		6 or 9	6 or 9	48
	incongruent	1 or 4	6 or 9	48
		6 or 9	1 or 4	48

In the awareness test, the same set of trials used in the number judgment task was presented. Instead of judging the target digits, participants were instructed to judge whether the prime digits were larger or smaller than five by clicking the "Large" or

"Small" button. There were 192 trials in the awareness test. To assess the visibility of primes, I calculated the *d'* in the awareness test (Macmillan & Creelman, 1996). Specifically, participants correctly judging a prime as larger than five was regarded as "hit", and incorrectly selecting "Large" when the prime was actually smaller than five was regarded as "false alarm." The influence of prime visibility on priming was investigated by regression analyses with priming magnitudes (i.e., $AUC_{incongruent}$ — $AUC_{congruent}$) on *d'*s.

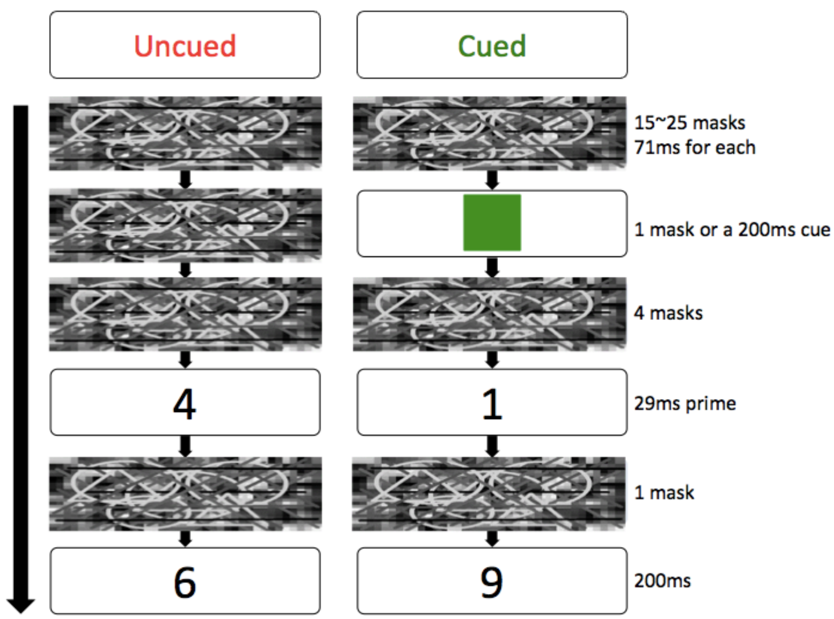


Figure 7. Procedures in the number judgment task. Participants were instructed to judge whether the target digit shown in the last frame was larger or smaller than five. Before the presentation of the target digit, a prime digit was flashed for 29ms followed by a mask. The only difference between cued and uncued conditions was that the second mask in the uncued condition was replaced by a cue (i.e., a green square) in the cued condition. In the cued condition, a prime was presented 413ms later after the onset of a cue. In the uncued condition, a prime was presented from 1420ms to 2130ms after the onset of the first mask.

3.1.4 Design

This experiment had a 2 (congruency: congruent vs. incongruent; within-subjects) × 2 (cue: cued vs. uncued; within-subjects) factorial design. For both cued and uncued conditions, analysis of variance (ANOVA) was applied to the AUCs obtained in the number judgment task to examine congruency effects (Figure 7).

3.1.5 AUC results

For the number judgment task, participant's response accuracy was at least 90 percent. In the cued condition, the average accuracy for congruent trials (M = 99.08 %) were marginally higher than that for incongruent trials (M = 98.59%); $t(41) = 1.99$, $p = 0.053$, $d = 0.62$, 95% CI_d [0.18, 1.06]. In the uncued condition, no difference was found between congruent (99.06%) and incongruent (98.71%) trials: $t(41) = 0.83$, $p = 0.41$, $d = 0.26$, 95% CI_d [-0.17, 0.69].

Figure 8 illustrates mean trajectories in the congruent and incongruent trials shown separately in the cued and uncued conditions.

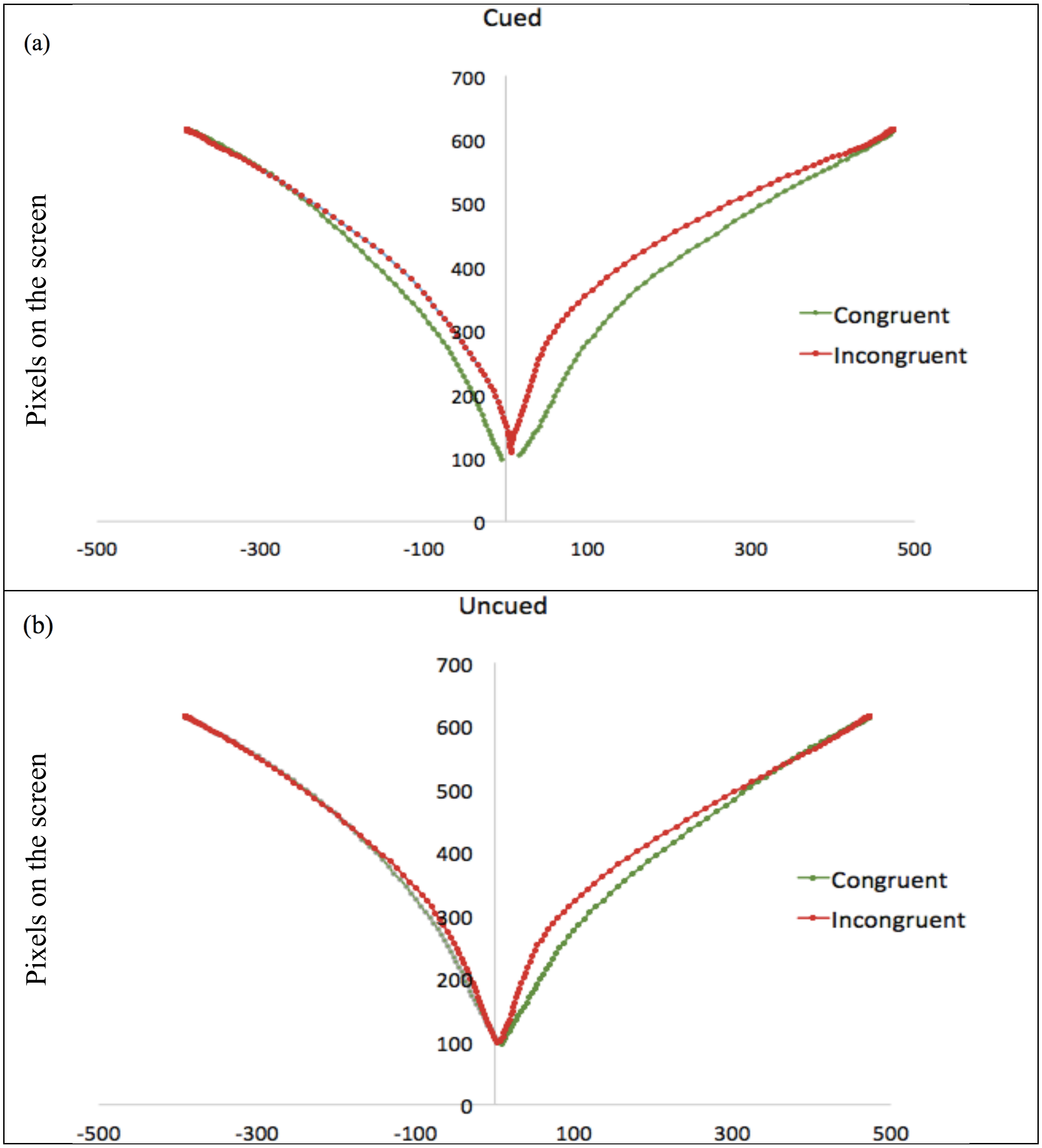


Figure 8. Average trajectories for congruent and incongruent trials. The X and Yaxes are scaled by amounts of pixels on the screen. Figure 8a shows average trajectories in the cued condition, and Figure 8b shows average trajectories in the uncued condition. Cursor locations were recorded from the onset of a prime until clicking the “Large” or “Small” button.

A two-way ANOVA (congruency × cue) for AUCs showed a significant main effect of congruency; $F(1, 41) = 23.92$, $MSE = 1608069.54$, $p < 0.001$, partial $\eta^2 = 0.37$. In both cued and uncued conditions, the AUCs were smaller in congruent than incongruent trials (Figure 9), indicating that participants experienced less semantic conflicts when responding to congruent trials than incongruent ones: in the cued condition, $t(41) = 4.63$, $p < 0.001$, $d = 1.44$, 95% CI_d [0.96, 1.92]; in the uncued condition, $t(41) = 2.96$, $p < 0.01$, $d = 0.92$, 95% CI_d [0.47, 1.37].

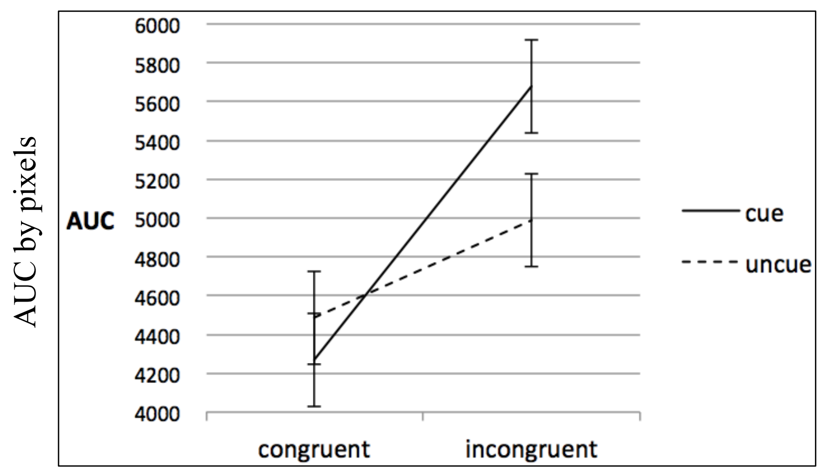


Figure 9. AUCs for congruent and incongruent trials. The error bars are two standard errors in length.

The two-way ANOVA also showed a significant interaction effect between congruency and cue, suggesting that the congruency effect was influenced by the presence / absence of the cue; $F(1, 41) = 9.07$, $MSE = 952417.85$, $p < 0.01$, partial $\eta^2 =$

0.18. To clarify the influence of cue, I compared AUCs between the cued and uncued conditions separately in congruent and incongruent trials.

A paired t-test revealed that AUCs in congruent trials in the cued (M = 4266.79, SD = 684.74) and uncued (M = 4486.79, SD = 725.43) conditions were statistically indistinguishable; $t(41) = 0.90$, $p = 0.37$, $d = 0.28$, 95% CI_d [-0.15, 0.71]. In contrast, AUCs in incongruent trials were significantly larger in the cued (M = 5677.39, SD = 711.25) than the uncued condition (M = 4990.15, SD = 714.41); $t(41) = 2.91$, $p < 0.01$, d = 0.91, 95% CI_d [0.46, 1.36]. These results suggest that presenting a cue helped accentuate the inconsistency but not the consistency between primes and targets. It seems that top-down attention probably made semantic conflicts between primes and targets more prominent.

3.1.6 Awareness analysis

To further explore whether the congruency effects occurred at a subliminal level, I calculated *d'* in the awareness test to measure the extent to which participants could identify the masked primes (Macmillan & Creelman, 1996). Here, I defined "hit" as participants making a "large" response when the prime digit was indeed larger than five and "false alarm" as participants making a "large" response when the prime was, in fact, smaller than five. This analysis suggests that the masked primes were hardly visible; the mean *d'* was not significantly different from zero in both the cued (M = 0.03, $t(41)$ = 1.28, $p = 0.21$) and uncued (M = 0.03, $t(41) = 1.56$, $p = 0.13$) conditions.

To probe the impact of prime visibility on the number judgment task, I performed a linear regression analysis with priming magnitudes (i.e., $AUC_{incongruent}$ —

AUC $_{congruent}$) on *d'*s (Greenwald, Draine, & Abrams, 1996). There was no correlation between the priming magnitudes and *d'*s in neither cued nor uncued condition, suggesting that the magnitude of priming was hardly influenced by the visibility of primes: in the cued condition, $b^* = -0.12$, $t(40) = 0.74$, $p = 0.46$; in the uncued condition, $b^* = -0.18$, $t(40) = 1.16$, $p = 0.25$. The regression analysis further revealed that intercepts were significantly above zero at null *d'*: in the cued condition, $b_0 = 1428.75$, $t(40) = 4.64$, $p < 0.001$; in the uncued condition, $b_0 = 519.05$, $t(40) = 3.06$, $p < 0.01$ (Figure 14).

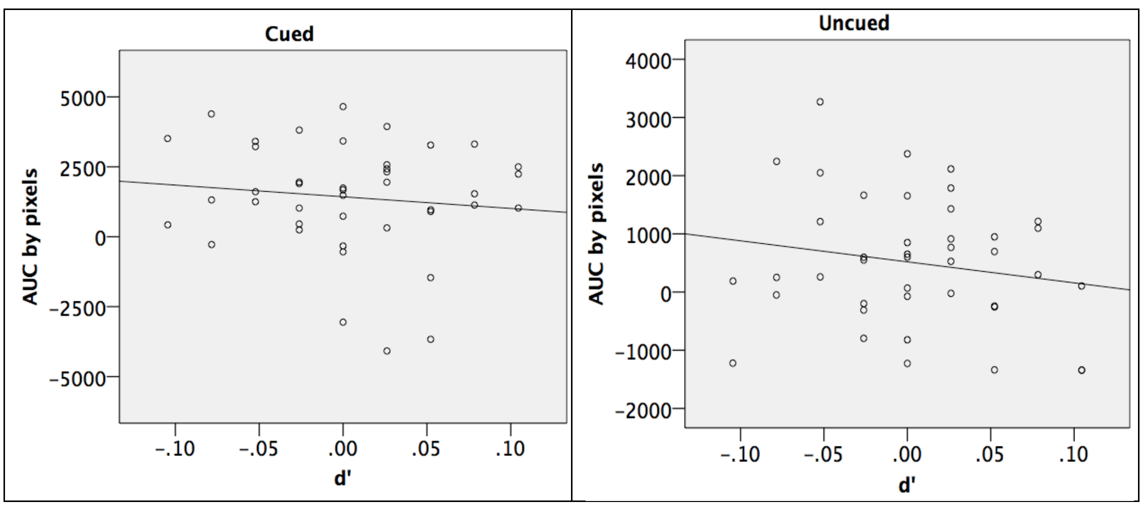


Figure 10. Regressions with priming magnitudes on *d'*s. The AUC is measured by amounts of pixels.

Additional analysis of d'. In Figure 10, *d'*s appear distributed categorically. For example, the x-axis of the left panel of Figure 10 shows that there are approximately 9 discrete values of *d'*. To investigate this potential "anomaly," I calculated all possible *d'* values observable in all awareness tests in Experiments 3-5. In the awareness test, there were 192 trials; among them, 96 trials had a prime larger than five, and the remaining 96 trials had a prime smaller than five. As discussed earlier, "hit" is defined as participants making a "large" response when the prime was indeed larger than five and "false alarm" is defined as participants making a "large" response when the prime was actually smaller than five. Ideally, a participant is expected to have 48 hits and 48 false alarms if the primes are invisible. In this case, *d'* is equal to zero, and *d'* reaches zero whenever the numbers of hits and false alarms are equal (e.g., (hit, false alarm) = (49, 49), (50, 50), (51, 51)).

In Experiments 3-5, the minimum number of observed hits was 43, and the maximum was 56; thus, there were 14 different numbers of hit. Similarly, the minimum number of observed false alarm was 44, and the maximum was 54; thus, there were 11 different numbers of false alarm. Since *d'* is determined by the numbers of hits and false alarms, there are 154 possible *d'* values at most in this range, corresponding to 154 (i.e., 14 × 11) combinations of hits and false alarms. Within this range of hits and false alarms, I calculated all 154 possible *d'*s in Figure 11.

Figure 11 shows the distribution of all 154 *d'*s arranged in ascending order from the smallest *d'* (i.e., -0.288) to the largest *d'* (i.e., 0.315). As the figure shows, the distribution of *d'* appears "categorical." Although this distribution looks categorical, the exact values of individual *d'* in the same "category" are slightly different; however, the differences are very small and visually indistinguishable (Figure 11). For example, when the numbers of hits and false alarms are different only by one trial (e.g., (hit, false alarm) = (45, 44), (46, 45), (47, 46), (48, 47),…, (55, 54)), *d'*s are nearly identical (e.g., (hit, false alarm; corresponding *d'*) = (46, 45; *d'* = 0.02622), (47, 46; *d'* = 0.02617), (48, 47; *d'* = 0.02613), (49, 48; *d'* = 0.02613),…, (55, 54; *d'* = 0.026494)). Similarly, when the numbers of hits and false alarms are different only by two trials, *d'*s are nearly identical (e.g., (hit, false alarm; corresponding *d'*) = (46, 44; *d'* = 0.0523883), (47, 45; *d'* = 0.0522987), (48, 46; *d'* = 0.0522452), (49, 47; *d'* = 0.0522274),…, (55, 53; *d'* = 0.0528771)). In other words, because the primes were barely visible in the awareness tests in Experiments 3-5, the number of hits and false alarms clustered in small ranges, yielding seemingly "categorical" distribution of *d'*s.

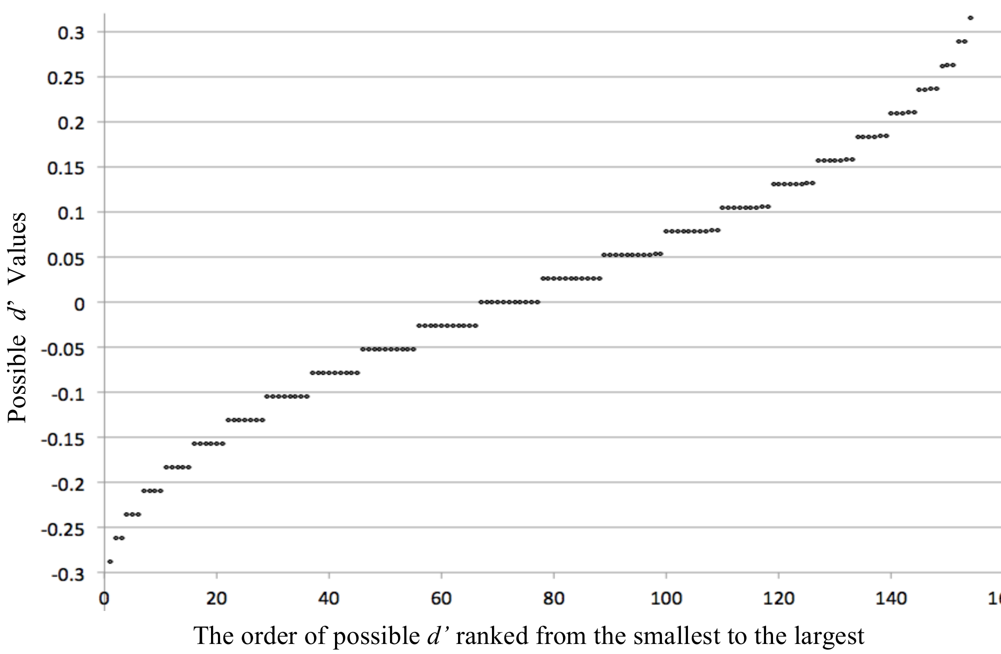


Figure 11. The distribution of all possible *d'*s. These possible *d'* values were obtained from all awareness tests in Experiments 3-5. The x-coordinate represents the order of *d'*s arranged in ascending order from the smallest *d'* to the largest *d'*, and the y-coordinate indicates the value of each *d'*. In Experiments 3-5, the number of hits ranges from 43 to 56, while the number of false alarms ranges from 44 to 54. In total, there are 154 possible combinations of hit and false alarm. This simulation suggests that *d'*s in the awareness tests appear "categorical" because primes were indeed barely visible.

In addition to *d'*s, I also calculated participants' response biases in the awareness test to examine if participants tended to make more positive or negative responses; a response bias *smaller* than one indicates more "yes" responses (i.e., bias toward "Large" in the this experiment), whereas a response bias *larger* than one indicates more "no" responses (i.e., bias toward "Small" in this experiment) (Macmillan & Creelman, 1996). Two one-sample t-tests show that the mean of response bias was larger than one in both the cued (M = 1.04, SD = 0.05, $t(41)$ = 3.63, $p < 0.001$) and uncued conditions (M = 1.03, SD = 0.04, $t(41)$ = 3.21, $p < 0.01$), suggesting that participants made more "Large" responses than "Small" responses in the awareness test.

3.1.7 Analysis of trajectory distance (TD)

In addition to AUC, I also analyzed the distance of cursor trajectories. In each trial, the trajectory distance (TD) is estimated by a summation of the Euclidean distance in each cursor motion step, and is measured by amounts of pixels. The analysis showed similar results as revealed by the AUC. A two-way ANOVA (congruency × cue) for TDs showed a significant main effect of congruency; $F(1, 41) = 13.69$, MSE = 4131.30, $p = 0.001$, partial $\eta^2 = 0.25$. In both cued and uncued conditions, the TD was shorter for congruent than incongruent trials: in the cued condition, $t(41) = 3.29$, $p = 0.002$, $d = 1.03$, 95% CI_d [0.57, 1.49]; in the uncued condition, $t(41) = 3.07$, $p = 0.004$, $d = 0.96$, 95% CI_d [0.51, 1.41]. No interaction between congruency and cue was found; $F(1, 41) = 1.30$, MSE = 1527.32, $p = 0.26$, partial $\eta^2 = 0.03$. To examine the influence of the cue, the cued and uncued conditions were compared separately for congruent and incongruent trials. A paired t-test indicated that TDs for congruent trials in the cued (*M* = 1167.63, *SD* = 288.68) and uncued (*M* = 1162.00, *SD* = 287.62) conditions were statistically indistinguishable; $t(41) = 0.69$, $p = 0.50$, $d = 0.22$, 95% CI_d [-0.21, 0.65]. However, the TDs for incongruent trials were significantly larger in the cued (*M* = 1211.19, *SD* = 319.99) than uncued condition (*M* = 1191.84, *SD* = 316.28); $t(41) = 2.23$, $p = 0.03$, $d = 0.70$, 95% CI_d [0.26, 1.14]. Again, the results suggest that top-down attention elicited by the cue most likely amplified semantic conflicts rather than consistency between primes and targets (Figure 12). There was no correlation between priming magnitudes and *d'*s in neither cued nor uncued condition, suggesting that the congruency effects were not influenced by prime visibility: the cued condition, $b^* = -0.06$, $t(40) = -0.38$, $p = 0.71$; the uncued condition, $b^* = 0.03$, $t(40) = 0.21$, $p = 0.84$. In addition, intercepts were significantly above zero at null *d'*: the cued condition, $b_0 = 43.12$, $t(40) = 3.22$, $p < 0.01$; the uncued condition, $b_0 = 30.01$, $t(40) = 3.04$, $p < 0.01$.

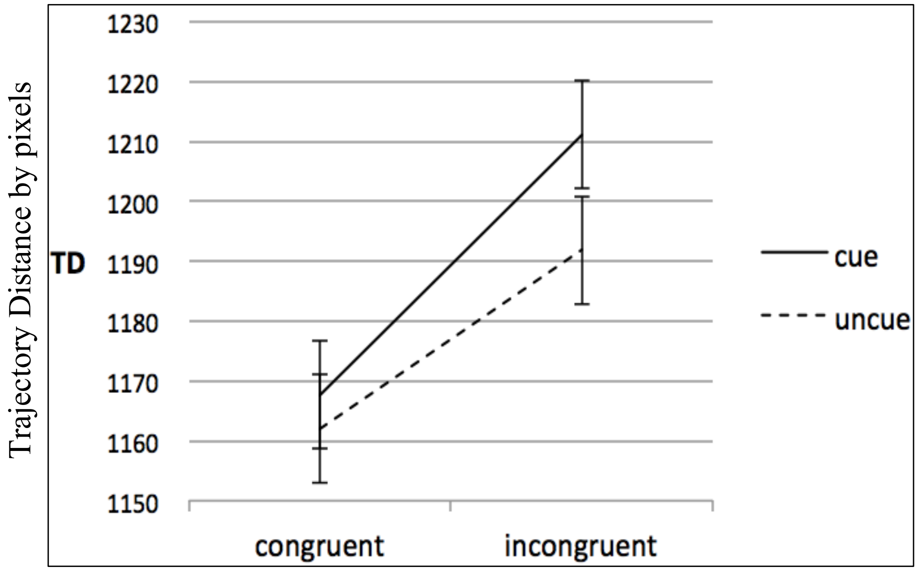


Figure 12. The trajectory distance (TD) for congruent and incongruent trials. The error bars are two standard errors in length. The trajectory distance (TD) is estimated by a summation of the Euclidean distance (measured by the amount of pixels) in each cursor motion step.

3.1.8 Analysis of cursor movement time (MT)

In addition to examining the spatial features of cursor motion data, I also analyzed a temporal feature assessed by cursor movement time (MT). The MT was defined as the time elapsed between the onset of the first cursor motion and a recorded click on either the "Large" or "Small" button. A two-way ANOVA (congruency × cue) for MTs showed a significant main effect of congruency; $F(1, 41) = 14.22$, MSE = 1646.46, $p = 0.001$, partial $\eta^2 = 0.26$. In the cued condition, MTs were smaller for congruent (M = 907.48, SD = 196.68) than incongruent (M = 934.34, SD = 201.60) trials: $t(41) = 2.85$, $p < 0.01$, $d = 0.89$, 95% CI_d [0.44, 1.34]; similarly in the uncued condition, MTs were smaller for congruent (M = 939.17, SD = 201.80) than incongruent (M =

959.54, *SD* = 206.33) trials: $t(41) = 2.75$, $p < 0.01$, $d = 0.86$, 95% CI_d [0.41, 1.31]. No interaction between congruency and cue were found; $F(1, 41) < 1$ (Figure 13). In addition, paired t-tests indicated that MTs were smaller in the cued than uncued conditions for both congruent and incongruent trials: congruent trials, $t(41) = 4.00$, $p < 0.001$, $d = 1.25$, 95% CI_d [0.78, 1.72]; incongruent trials, $t(41) = 2.94$, $p < 0.01$, $d = 0.92$, 95% CI_d [0.47, 1.37]. There was no correlation between priming magnitudes and *d'*s in neither cued nor uncued condition, suggesting that the congruency effects were not influenced by prime visibility: the cued condition, $b^* = 0.15$, $t(40) = 0.93$, $p = 0.36$; the uncued condition, $b^* = -0.03$, $t(40) = -0.19$, $p = 0.85$. In addition, intercepts were significantly above zero at null *d'*: the cued condition, $b_0 = 27.63$, $t(40) = 2.91$, $p < 0.01$; the uncued condition, $b_0 = 20.24$, $t(40) = 2.69$, $p = 0.01$.

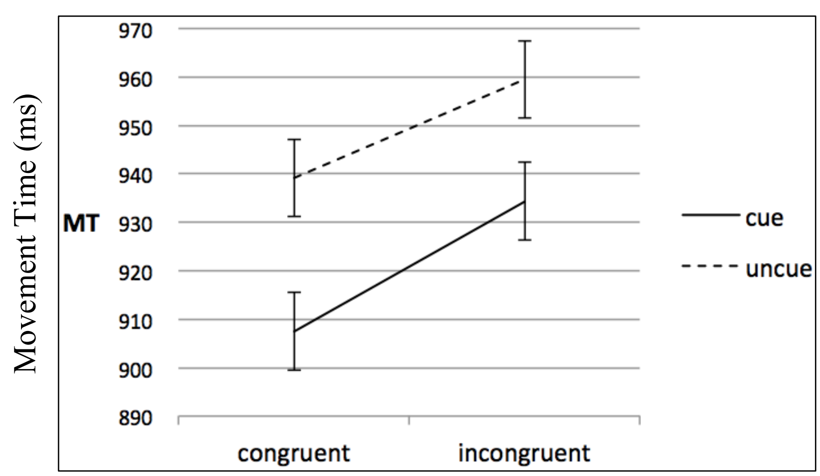


Figure 13. The movement time (MT) for congruent and incongruent trials. The error bars are two standard errors in length.

3.1.9 Analysis of initiation time (IT)

Another important temporal feature is the initial time (IT), which is the time elapsed from the onset of the presentation of a prime digit to the onset of the first cursor motion in each trial. A two-way ANOVA (congruency × cue) for ITs showed no main effect of congruency; $F(1, 41) < 1$. No interaction between congruency and cue was found; $F(1, 41) = 2.58$, $MSE = 446.44$, $p = 0.12$, partial $\eta^2 = 0.06$. Paired t-tests showed that in the uncued condition, ITs were smaller for congruent ($M = 99.50$, $SD = 77.43$) than incongruent ($M = 107.12$, $SD = 85.04$) trials: $t(41) = 2.05$, $p < 0.05$, $d = 0.64$, 95% CI_d [0.20, 1.08]; however in the cued condition, mean ITs were not statistically different between congruent ($M = 92.93$, $SD = 71.93$) and incongruent ($M = 90.07$, $SD = 71.95$) trials: $t(41) = 0.61$, $p = 0.54$, $d = 0.19$, 95% CI_d [-0.24, 0.62] (Figure 14). Further t-tests indicated that ITs were smaller in the cued than uncued conditions only for incongruent but not for congruent trials: for incongruent trials, $t(41) = 3.19$, $p < 0.01$, $d = 1.00$, 95% CI_d [0.55, 1.45]; for congruent trials, $t(41) = 1.81$, $p = 0.08$, $d = 0.57$, 95% CI_d [0.13, 1.01]. There was no correlation between priming magnitudes and *d'*s in neither cued nor uncued condition, suggesting that prime visibility did not influence the magnitude of congruency: in the cued condition, $b^* = 0.10$, $t(40) = 0.64$, $p = 0.52$; in the uncued condition, $b^* = -0.13$, $t(40) = -0.85$, $p = 0.40$. Intercepts were not significantly above zero at null *d'*: in the cued condition, $b_0 = -2.60$, $t(40) = -0.55$, $p = 0.59$; in the uncued condition, $b_0 = 7.35$, $t(40) = 1.96$, $p = 0.06$.

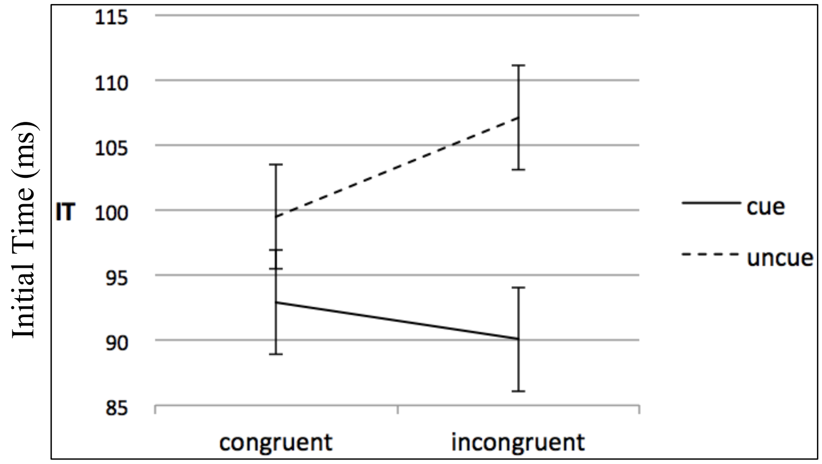


Figure 14. The initial time (IT) for congruent and incongruent trials. The error bars are two standard errors in length.

3.1.10 Discussion

By applying the cursor motion method directly to the number judgment task employed in the Naccache et al. (2002) study, I examined the extent to which top-down attention influenced subliminal semantic priming in two conditions — cued and uncued. In the uncued condition, the pre-target duration changed randomly trial-by-trial; in the cued condition, a cue was presented with a fixed duration before targets to signal the upcoming target. Therefore, participants' top-down attention to targets and primes was disrupted in the uncued condition (because the random time window made it difficult for the participant to anticipate when a target would appear), while it was facilitated in the cued condition.

Consistent with the Naccache et al. (2002) findings, a significant congruency effect was observed in the cued condition; however, inconsistent with their findings, a significant congruency effect was also present in the uncued condition. These results suggest that subliminal semantic priming can still occur in near absence of attention, favoring the explanation that automatic semantic processing can produce priming effects without much assistance of top-down attention.

Why is the cursor motion measure more sensitive to subliminal semantic processing than the response time measure? Temporal measures, such as response time, movement time, and initial time, only make use of two data points in each trial: the onset time and the end time. Thus, any intervening factors that occur in-between can be glossed over. For example, imagine flight information from New York City to Tokyo. The response time data yield the duration of the flight, such as 15 hours and 20 minutes. From this data, it is nearly impossible to infer the exact route of the flight or the condition of the flight. Did the airplane stop over Los Angeles, San Francisco, or Anchorage? Or was the flight delayed because of the bad weather in Alaska or Colorado? Given the discrete temporal data — the departure time and the arrival time — one can hardly infer what happened in-between. In contrast, the cursor motion measure provides minutes by minutes information about the location of the airplane. From this data set, it is relatively easy to infer the factors that influenced the flight.

The same rationale explains the advantage of AUC over trajectory distance (TD). Although both AUC and TD make use of temporal-spatial data points in each trial, the AUC includes all pixels in the area circumscribed by the cursor trajectory, whereas the TD only includes pixels on the edge of the circumscribed area. Thus, AUC is more informative than TD because AUC helps characterize how primes and targets interact continuously.

In summary, subliminal semantic processing can be modulated by cognitive control, and can still occur with little assistance from top-down attention. Top-down attention helps priming but may not be necessary for subliminal semantic processing. In Experiment 4 and 5, factors such as cue colors and SOAs were examined, and priming effects were exclusively measured by AUCs.

3.2 Experiment 4

Experiment 4 examined the source of the amplified congruency effect in the cued condition in the Naccache et al. (2002) study. Did the green cue enhance the congruency effect by means of top-down attention or as an indirect prime? Experiment 1 shows that a green-colored priming picture (e.g., a green light) facilitates positive judgment (i.e., “same” judgment) and impede negative judgment (i.e., “different” judgment), while a red-colored priming picture (e.g., a red light) facilitate negative judgment and impede positive judgment. This suggests that colors of primes could influence the number judgment task.

Following this rationale, the green cue employed in Experiment 3 as well as in the Naccache et al. (2002) study might have worked as an indirect prime rather than a “cue” for attention trigger. Thus, the role of top-down attention for subliminal semantic priming is still uncertain. Experiment 4 addressed this question by contrasting two between-subjects conditions — a green cue condition and a red cue condition. The design of Experiment 4 was identical to Experiment 3 except that an additional between-subjects condition (i.e., the red cue condition) was augmented to Experiment 3. As in Experiment 3, Experiment 4 had a 2 (congruency: congruent vs. incongruent; within-subjects) $\times$ 2 (cue: cued vs. uncued; within-subjects) factorial design. However, we conducted the same experiment twice with different cue colors (between-subjects factor), one with a green cue and the other with a red cue.

If the cue color (green), rather than the cue itself, was solely responsible for the amplified congruency effect in Experiment 3, the advantage of the cue should be eliminated when the green cue is replaced with a red cue. In contrast, if top-down attention triggered by a cue is the source of the enhanced congruency effect in the cued condition in Experiment 3, enhanced congruency effects should emerge both in the red cue and green cue conditions.

3.2.1 Participants

A total of 82 undergraduate students from Texas A&M University participated in this experiment for course credits. These participants were randomly assigned to the green cue (n = 41) condition or the red cue condition (n = 41). Four participants in the green cue condition and one participant in the red cue condition did not complete the awareness test. Thus, the data from 77 participants (n = 37 in the green cue condition and n = 40 in the red cue condition) was analyzed.

3.2.2 Materials and apparatus

A 70 Hz monitor was used to present stimuli, and the experimental procedures were controlled by a customized computer program developed with Microsoft Visual Studio.

3.2.3 Procedure

The procedure and stimuli were identical to those described in Experiment 3, except for the color of cues: the cue was red in the red cue condition while green in the green cue condition (Figure 15).

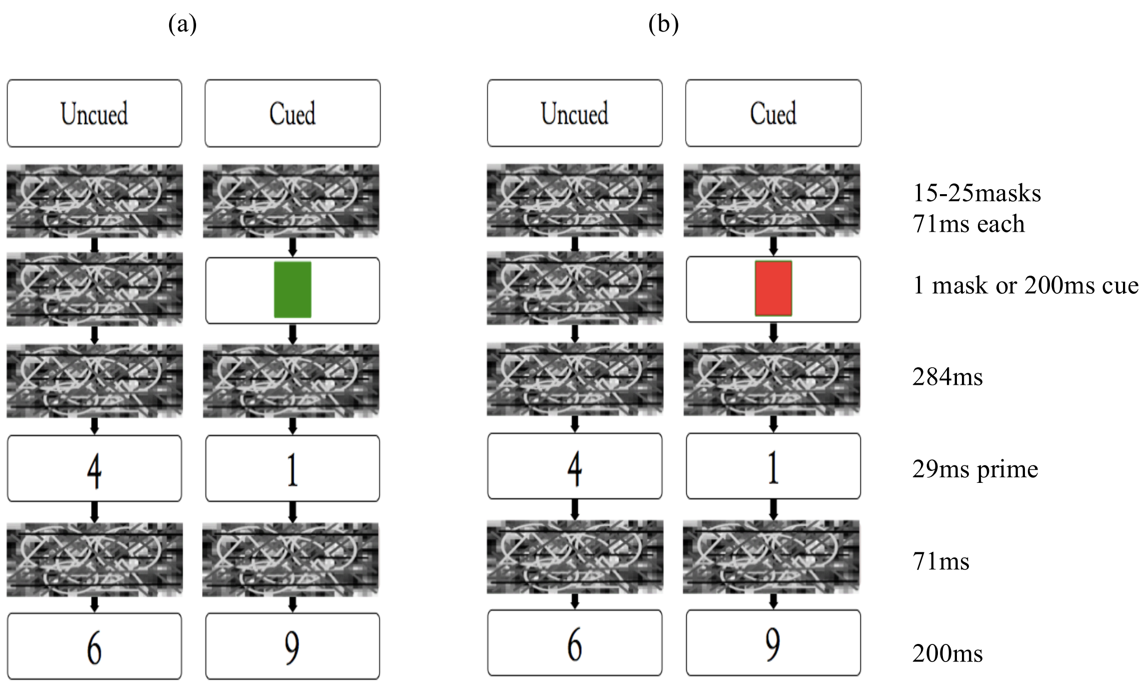


Figure 15. Procedures in the green and red cue conditions. The only difference between the green and red cue conditions is the color of cues: either green or red.

3.2.4 Design

Experiment 4 was designed with three factors: cue color (green cue, red cue; between-subjects), cue (cued, uncued; within-subjects), and congruency (congruent, incongruent; within-subjects). Since the cue color was nested in the cued condition, it was improper to perform a three-way ANOVA on these three factors. Thus, a two-way ANOVA (cue × congruency) was performed to reveal the effects of attention and congruency, and a two-way ANOVA (cue color × congruency) was performed to examine the effect of cue color.

3.2.5 AUC results

3.2.5.1 Impacts of attention on congruency

Cue × Congruency. As predicted, AUC was significantly smaller in the congruent trials than in the incongruent trials. There was a main effect of congruency ($F(1, 75) = 38.74$, $MSE = 976662.63$, $p < 0.001$, partial $\eta^2 = 0.34$), indicating that semantic congruency influenced the number judgment. An interaction effect between cue and congruency further suggests that the congruency effect was amplified when a cue was presented: $F(1, 75) = 9.09$, $MSE = 610495.37$, $p < 0.01$, partial $\eta^2 = 0.11$. The magnitude of priming was significantly larger in the cued condition: $M = 1174.86$, $SD = 191.70$) than in the uncued condition ($M = 482.53$, $SD = 194.17$); $t(36) = 2.69$, $p < 0.01$, $d = 0.90$, 95% CI_d [0.42, 1.38].

3.2.5.2 Impacts of cue color on congruency

Cue color × Congruency. To examine the extent to which cue color influenced congruency effects, a two-way ANOVA (cue color × congruency) was applied only to the cued condition because two levels of cue color, green and red, were present in the cued condition but not in the uncued condition. As predicted, AUC was significantly smaller in the congruent trials than in the incongruent trials; the main effect of congruency ($F(1, 75) = 37.6$, $MSE = 962178.54$, $p < 0.001$, partial $\eta^2 = 0.33$). The main effect of congruency was observed both in the green cue and red cue conditions; the green cue condition, $F(1, 36) = 33.24$, $MSE = 764431.74$, $p < 0.001$, partial $\eta^2 = 0.48$; the red cue condition, $F(1, 39) = 11.25$, $MSE = 1172568.07$, $p < 0.01$, partial $\eta^2 = 0.22$ conditions.

Overall, we found no interaction effect between cue color and congruency, ($F(1, 75) = 1.67$, $MSE = 962178.54$, $p = 0.20$, partial $\eta^2 = 0.02$), suggesting that cue color did not influence the magnitude of congruency effects. In addition, the main effect of cue color was not significant; $F(1, 75) = 2.59$, $MSE = 18324130.50$, $p = 0.11$, partial $\eta^2 = 0.03$. Taken together, the results suggest that the cue color itself did not influence the magnitude of congruency effect.

3.2.5.3 The AUC difference between green and red cue conditions

Although the cue color did not change the congruency effects, overall AUCs were larger in the red cue condition ($M = 4497.70$, $SD = 2914.21$) than in the green cue condition ($M = 3181.47$, $SD = 2764.01$); $t(75) = 2.03$, $p < 0.05$, $d = 0.47$, 95% CI_d [0.02, 0.92] (Figure 16). This suggests that when the red cue was given, participants were more likely to deviate toward the unselected option before making the final choice irrespective of the congruency / incongruency of the prime.

In comparing the impact of cues in the red and green cue conditions separately, we found that a cue amplified the congruency effect significantly when the green cue was given; the interaction between cue and congruency was present in the green cue condition ($F(1, 36) = 7.23$, $MSE = 612879.43$, $p = 0.01$, partial $\eta^2 = 0.17$). However, providing a red cue did not increase the congruency effect much; the interaction between cue and congruency did not reach a significant level in the red cue condition ($F(1, 39) = 2.41$, $MSE = 608294.71$, $p = 0.13$, partial $\eta^2 = 0.06$). Further paired t-tests suggested that the cue primarily amplified congruency effects in the green cue condition: the priming magnitude (i.e., $AUC_{incongruent} — AUC_{congruent}$) was larger in the cued condition ($M = 1174.86$, $SD = 191.70$) than in the uncued condition ($M = 482.53$, $SD = 194.17$); $t(36) = 2.69$, $p < 0.01$, $d = 0.90$, 95% CI_d [0.42, 1.38]. Such amplification effect of attention was not significant in the red cue condition ($t(39) = 1.55$, $p = 0.13$, $d = 0.50$, 95% CI_d [0.04, 0.96]).

The AUC difference between the red cue and green cue conditions suggests that the cue color influences participants' cursor motion in decision making to some extent regardless of the congruency / incongruency of the prime-target relation. This influence is discussed in detail in the Discussion section.

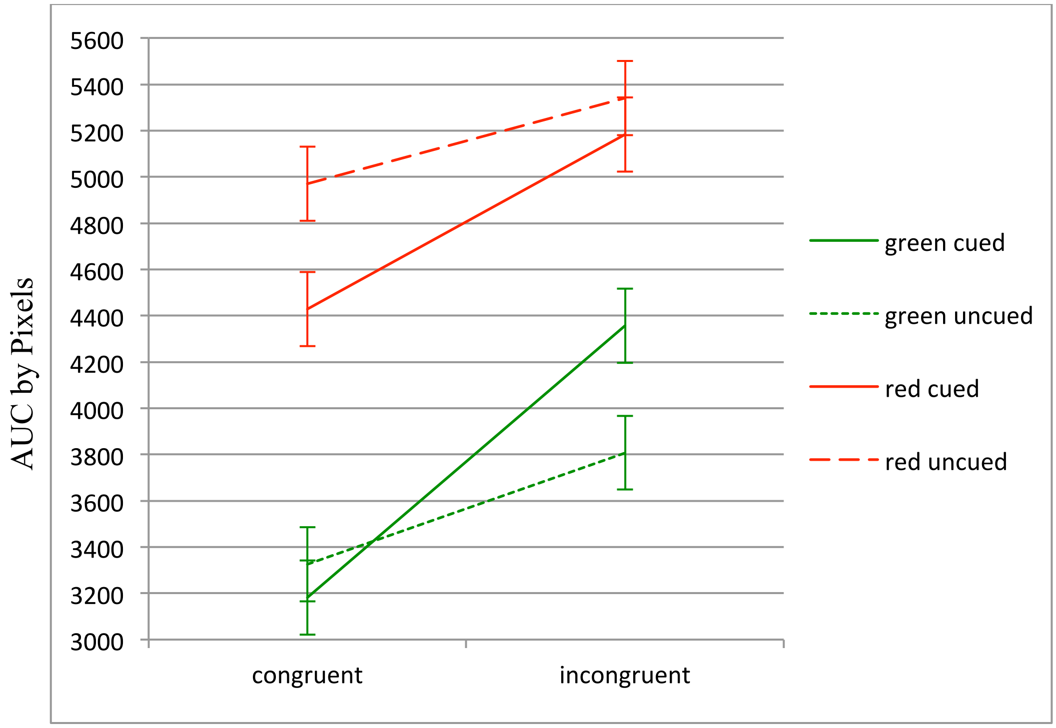


Figure 16. AUCs in the green and red cue conditions. The error bars are two standard errors in length.

3.2.6 Awareness results

In the awareness test, the *d'*s were not significantly different from zero: in the green cue condition, $M = 0.005$, $t(36) = 0.61$, $p = 0.54$; in the red cue condition, $M = 0.004$, $t(39) = 0.49$, $p = 0.63$ (Stanislaw & Todorov, 1999). Linear regressions showed no correlation between the priming magnitudes and *d'*s in neither cued nor uncued conditions (Table 12 & 13), suggesting that the priming effects were not influenced by participants' awareness of the masked primes. Furthermore, intercepts were significantly higher than zero at null *d'*, suggesting that the congruency effect was still significant for participants who could not see the masked primes at all (Table 12 & 13; Figure 17 & 18).

Table 12 Regressions with priming magnitudes on *d*'s for the green cue

		B	*t*	*p*
Cued	*constant*	1175.88	6.02	<0.001
	d'	-0.01	-0.05	0.96
Uncued	*constant*	462.47	2.37	0.02
	d'	0.17	1.01	0.32

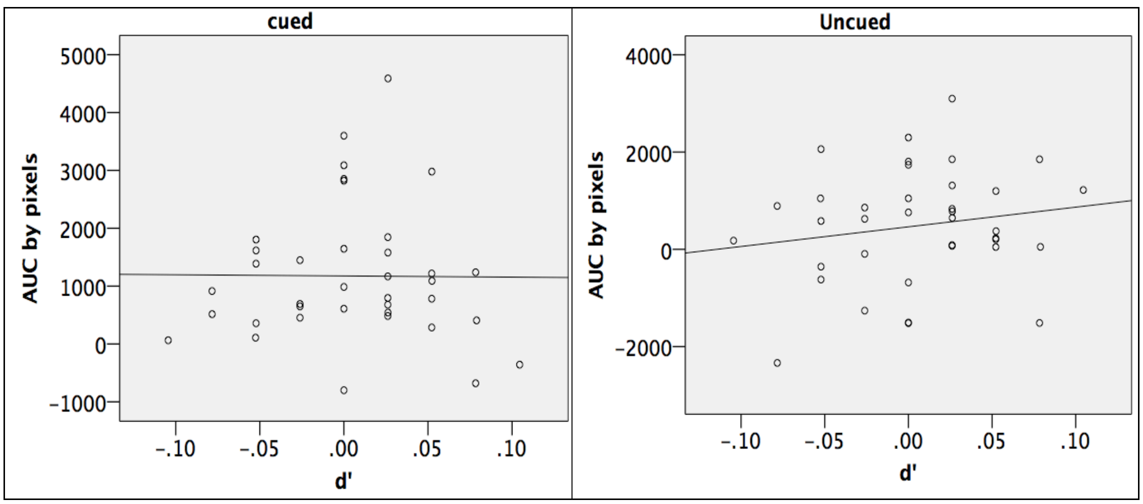


Figure 17. Regressions with priming magnitudes on *d*'s for the green cue. The AUC is measured by amounts of pixels.

Table 13 Regressions with priming magnitudes on *d*'s for the red cue

		B	*t*	*p*
Cued	*constant*	753.00	3.01	<0.01
	d'	0.10	0.64	0.53
Uncued	*constant*	366.19	2.20	0.03
	d'	0.21	1.29	0.21

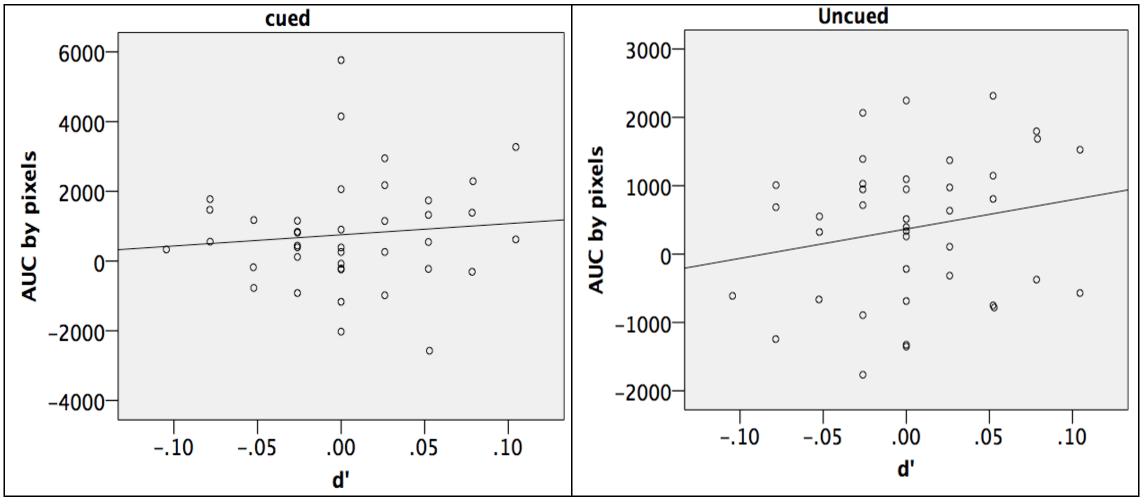


Figure 18. Regressions with priming magnitudes on *d*'s for the red cue. The AUC is measured by amounts of pixels.

In addition, analyses of response bias indicated that participants' were not biased towards "Large" or "Small" responses: in the green cue condition, $M = 0.994$, $SD = 0.065$, $t(36) = 0.60$, $p = 0.56$, $d = 0.20$, 95% CI_d [-0.26, 0.66]; in the red cue condition, $M = 0.993$, $SD = 0.069$, $t(39) = 0.65$, $p = 0.52$, $d = 0.21$, 95% CI_d [-0.23, 0.65]. There was no difference of response biases between the green and red cue conditions; $t(75) = 0.04$, $p = 0.97$.

3.2.7 Discussion

Experiment 4 examined whether cue colors influenced subliminal semantic processing. Results in the green cue condition are consistent with those in Experiment 3. AUCs were smaller in congruent trials than in incongruent trials, and the priming magnitude was larger in the cued condition than in the uncued condition, suggesting that presenting a cue indeed amplified subliminal semantic processing. As in Experiment 3, congruency effects are still significant in the uncued condition, supporting the view that subliminal semantic processing can occur in near absence of attention. Taken together, these results suggest that the assistance from top-down attention helps but is not necessary for subliminal semantic processing to occur.

In the red cue condition, congruency effects are significant in both the cued and uncued conditions, indicating that subliminal semantic processing occurs without assistance of top-down attention, which is consistent with results in the green cue condition. However, the priming magnitude in the cued condition was not significantly larger than that in the uncued condition, suggesting that the amplification effect of top-down attention was weaker when the cue was red.

Although there is no two-way interaction between cue color and congruency, a large AUC difference between the green and red cue conditions suggests that cue color influenced the overall decision process. This suggests that the red cue possibly worked as an indirect prime. My tentative explanation is that participants probably associated the red cue with “alarm,” “alert,” and “stop;” as a result, the red cue made participants more cautious and hesitant, resulting in larger AUCs. Admittedly, there are other potential interpretations for the role of cue color. Since effects of congruency, attention, and cue color are mixed, how cue color alone influences priming cannot be explained in a straightforward way. Clearly, more research is needed to scrutinize the role of cue color for sematic priming.

To summarize, the cue color influences priming to some extent. On the other hand, the influence of cue color is relatively limited, compared to the strong effect of semantic congruency. Although the congruency effect was greater in the green cue condition than in the red cue condition, a significant congruency effect was still present in the red cue condition. This suggests that the amplified congruency effects in the cued condition cannot be attributed solely to the color of the cue. Although the cue color influences overall response patterns, the fact that the congruency effect is present both in the green and red cue conditions suggest that the presence of a cue, not just its color, facilitated semantic congruency, favoring the view that top-down attention triggered by the cue influenced the congruency effect independently of cue color. In Experiment 5, I focused on a green cue and investigated temporal characteristics of top-down attention in subliminal semantic processing.

3.3 Experiment 5

One important question regarding the role of top-down attention for subliminal semantic processing is its time course. Top-down attention is said to amplify semantic priming (Naccache et al., 2002; Dehaene et al., 2005; 2006); yet how exactly it influences subliminal processing remains unclear. Naccache et al. (2002) applied a fixed 100ms stimulus-onset asynchrony (SOA) in their study; because of this constraint, their study only provides partial time course of semantic priming. In Experiment 5, I manipulated the duration from the onset of primes to the onset of targets (i.e., stimulus-onset asynchrony — SOA) and investigated the impact of top-down attention on subliminal semantic processing.

Experiment 5 was identical to Experiment 3 (see also Naccache et al. 2002) except for one minor modification. As in Experiment 3, participants in Experiment 5 judged whether a target digit (e.g., “9”) was larger or smaller than five, preceded by a masked priming digit (e.g., “6”) in the cued or uncued conditions (within-subjects). Participants carried out the number judgment task under four SOA conditions: 50ms, 200ms, 500ms, and 1000ms (between-subjects), where the duration from the onset of the prime to the onset of the target (i.e., SOA) was changed accordingly.

I expect that top-down attention influences subliminal priming at least in three different manners: (1) top-down attention amplifies and extends semantic priming; (2) top-down attention amplifies priming without extending the lifespan of priming; and (3) top-down attention prompts semantic priming earlier without amplifying or extending semantic priming.

If (1) top-down attention amplifies and extends semantic priming, cued trials would elicit substantial congruency effects for all four SOAs, and the magnitude of priming would be larger in the cued condition than in the uncued condition for all four SOAs (Figure 19).

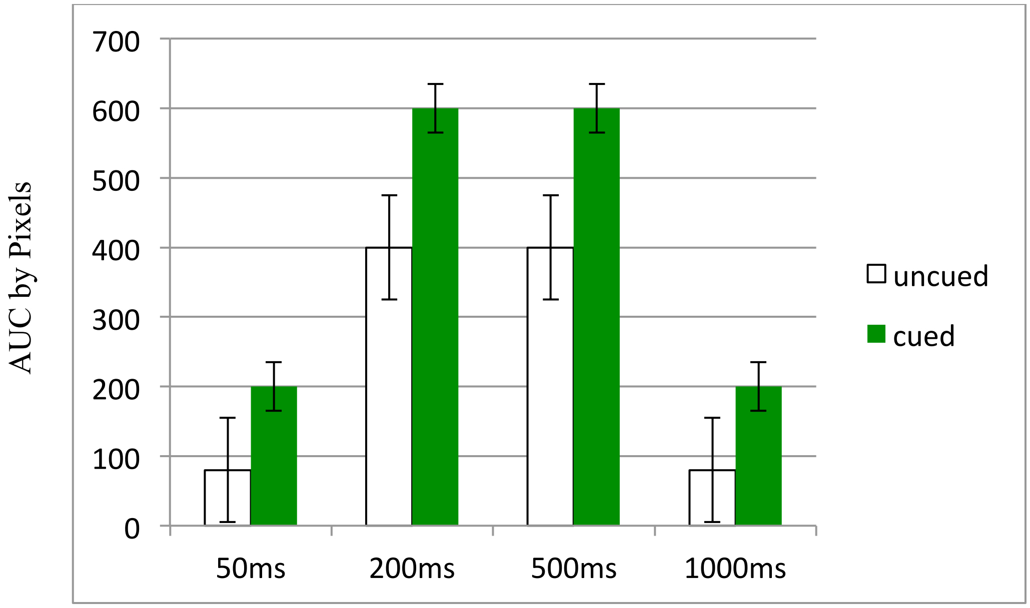


Figure 19. Prediction (1). Top-down attention amplifies and extends subliminal semantic processing.

If (2) top-down attention amplifies priming without extending the lifespan of priming, presenting a cue would amplify priming only for medium SOAs (e.g., 200ms and 500ms) but not for very short (e.g., 20ms) or very long (e.g., 1000ms) SOA (Figure 20).

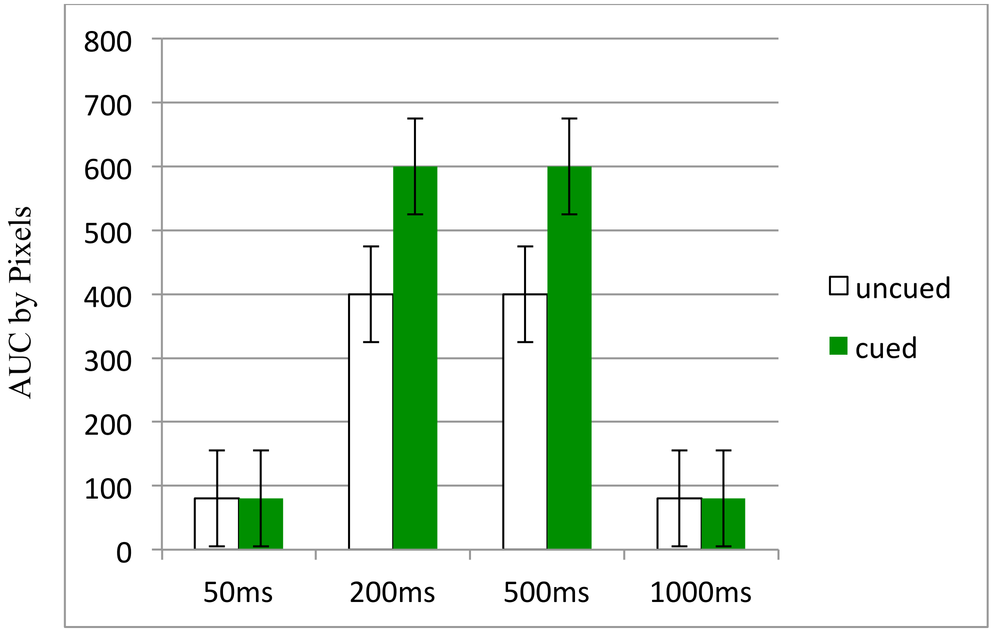


Figure 20. Prediction (2). Top-down attention amplifies priming without extending the lifespan of priming.

If (3) top-down attention makes priming occur earlier without amplifying or extending subliminal semantic processing, the largest congruency effect would be observed earlier in the cued condition (e.g., 200ms SOA) than in the uncued condition (e.g., 500ms SOA). Accordingly, congruency effects would recede earlier in the cued condition (e.g., 500ms SOA) than in the uncued condition (e.g., 1000ms SOA). That is, presenting a cue makes semantic priming occur earlier and fade away earlier; yet it neither amplifies nor extends semantic priming (Figure 21).

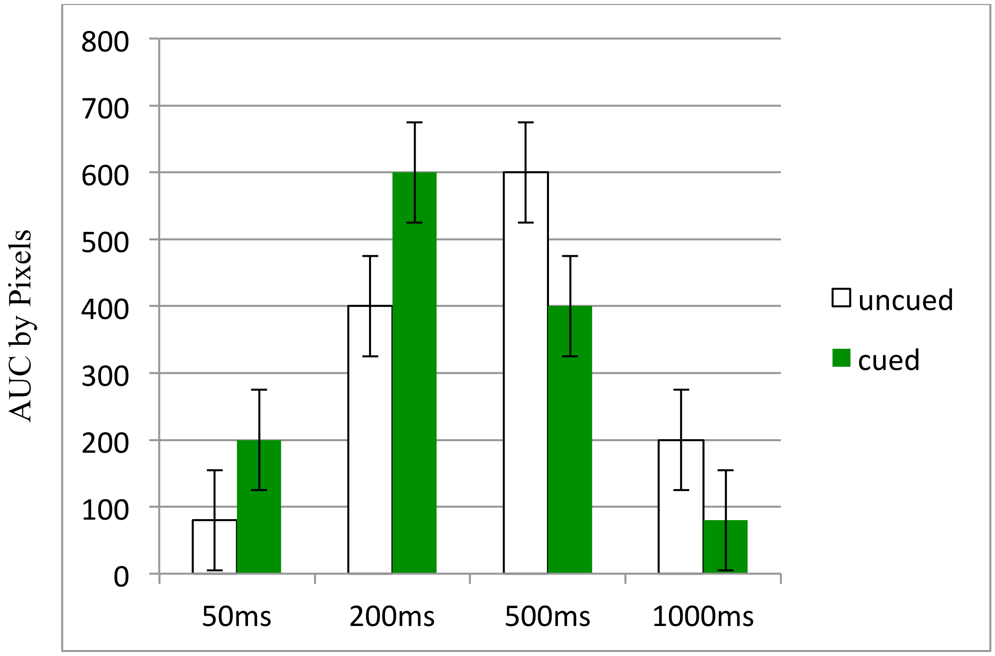


Figure 21. Prediction (3). Top-down attention shift priming forward without amplifying or extending priming.

Experiment 5 examined both the global workspace theory and the temporal attention window theory. According to the global workspace theory (Dehaene et al., 1998; 2005; 2006), top-down attention is *necessary* for subliminal semantic processing; this view, however, would be challenged if significant congruency effects were found in the uncued condition. The global work theory (Dehaene et al., 2005; 2006) also suggests that the temporal attention triggered by signaling stimuli has a very limited lifespan of only a few hundred milliseconds. Specifically, according to the temporal attention window (TAW) hypothesis (Naccache et al., 2002, Dehaene et al., 2005), the top-down attention window lasts for approximately 500ms (i.e., the duration from the onset of the cue to the onset of the prime), which amplifies subliminal semantic processing. Yet, it is unclear whether the temporal attention window (TAW) covers the prime only or covers both the prime and the target, because interval between the prime and target was very brief (i.e., 100ms SOA) in the Naccache et al. (2002) study. While in Experiment 5, the duration from the onset of the cue to the onset of the target is more than 1000ms for 500ms SOA. If the TAW hypothesis is correct, priming should be weakened for 500ms SOA. In contrast, if the temporal attention window lasts for more than 1000ms, semantic priming should be observed for 500ms SOA (or even for 1000ms SOA if the temporal attention window lasts for more than 1500ms). If this is true, temporal attention both prolongs and enhances subliminal semantic processing, and the lifespan of temporal attention is far longer than what is suggested by the temporal attention window theory.

3.3.1 Participants

A total of 183 undergraduate students from Texas A&M University participated in this experiment for course credits. One participant in the 50ms condition, one participant in the 200ms condition, two participants in the 500ms condition, and one participant in the 1000ms condition were excluded from data analysis because their response accuracy was lower than 80%. In total, the data from 178 participants was analyzed (n = 45 in the 50ms SOA condition; n = 45 in the 200ms SOA condition; n = 45 in the 500ms SOA condition; and n = 43 in the 1000ms SOA condition).

3.3.2 Materials and apparatus

A 70 Hz monitor was used to present stimuli, and the experimental procedures were controlled by a customized computer program developed with Microsoft Visual Studio.

3.3.3 Procedure

Participants were randomly assigned to one of four SOA conditions: 50ms, 200ms, 500ms, 1000ms. The procedures were identical to those described in Experiment 3 except for different SOAs (Figure 22).

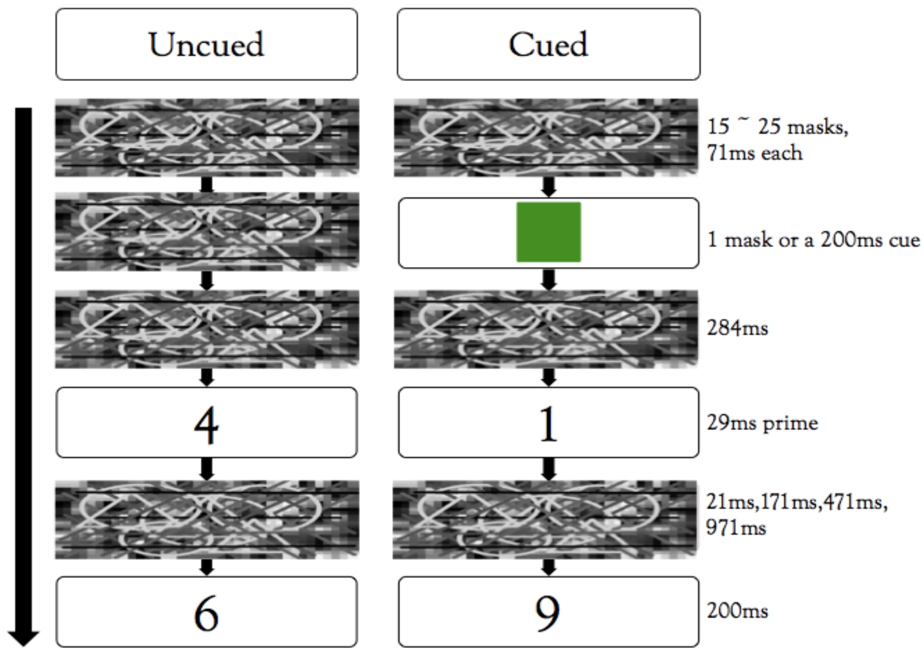


Figure 22. The post-prime mask durations vary among four SOA conditions.

3.3.4 Design

Experiment 5 had a 4 (SOA: 50ms, 200ms, 500ms, 1000ms; between-subjects) × 2 (cue: cued, uncued; within-subjects) × 2 (congruency: congruent, incongruent; within-subjects) factorial design.

3.3.5 Results

3.3.5.1 Overall congruency effects

A three-way ANOVA (congruency × cue × SOA) showed a significant main effect of congruency (congruent trials, *M* = 5713.03, *SD* = 4317.69; incongruent trials, *M* = 6046.36, *SD* = 4417.42); $F(1, 174) = 23.00$, $MSE = 24457561.60$, $p < 0.001$, partial $\eta^2 = 0.12$. There was also a significant two-way interaction (congruency × SOA) effect; $F(3, 174) = 4.73$, $MSE = 5025525.58$, $p < 0.01$, partial $\eta^2 = 0.08$. Paired t-tests examining congruency effects for each SOA (collapsing cued and uncued conditions) demonstrated significant congruency effects for 50ms and 200ms SOA, and a marginally significant congruency effect for 500ms SOA (Table 14). The two-way interaction between congruency and cue was marginally significant (Figure 23); $F(1, 174) = 3.13$, $MSE = 930928.26$, $p = 0.08$, partial $\eta^2 = 0.02$.

Table 14 Congruency effects with cued and uncued conditions collapsed

SOA	*N*	Congruent	Incongruent	*t*	*p*	Cohen's *d*
50	45	4604.24	5051.14	2.23	0.03	0.67
200	45	5789.97	6433.69	4.31	<0.001	1.30
500	45	5417.11	5776.14	1.90	0.06	0.57
1000	43	7102.55	6965.29	-0.82	0.42	0.25

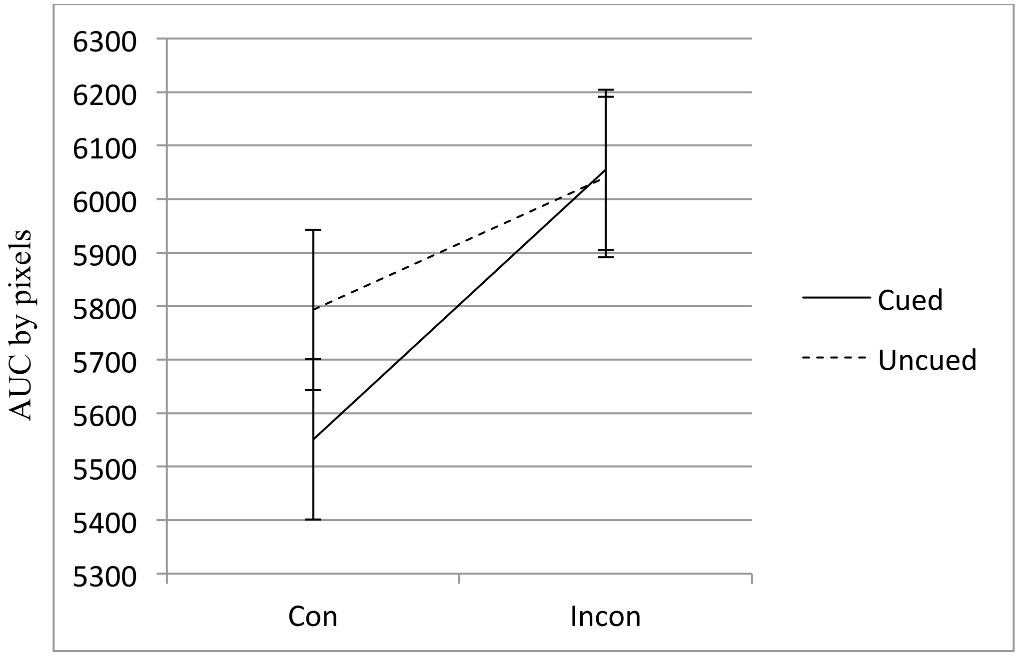


Figure 23. Congruency effects with all SOAs collapsed. The AUC is measured by amounts of pixels. The error bars are two standard errors in length.

Although there was no three-way (congruency × cue × SOA) interaction effect (F(3, 174) = 1.25, MSE = 930572.59, p = 0.30, partial η^2 = 0.02), additional t-tests were performed to show congruency effects in each SOA separately for the cued and uncued conditions. The purpose of these t-tests is to provide complementary information of congruency effects. As shown in Table 15 &16, significant congruency effects were observed in the 50ms, 200ms, and 500ms SOAs in the cued condition and in the 200ms SOA in the uncued condition.

Table 15 Congruency effects (AUC by pixels) in the cued condition

SOA	*N*	Congruent	Incongruent	*t*	*p*	Cohen's *d*
50	45	4731.15	5045.9	2.02	<0.05	0.61
200	45	5460.02	6475.95	7.18	<0.001	2.16
500	45	5215.27	5802.04	3.78	<0.001	1.14
1000	43	6859.38	6936.74	0.35	0.73	0.11

Note. The AUC is measured by amounts of pixels.

Table 16 Congruency effects (AUC by pixels) in the uncued condition

SOA	*N*	Congruent	Incongruent	*t*	*p*	Cohen's *d*
50	45	4540.79	5053.77	1.73	0.09	0.52
200	45	5954.95	6412.57	2.09	0.04	0.63
500	45	5518.03	5763.18	0.96	0.34	0.29
1000	43	7224.14	6979.57	-1.21	0.23	0.37

Note. The AUC is measured by amounts of pixels.

3.3.5.2 The time course of congruency effects

To investigate the time course of congruency effects further, we calculated the priming magnitude (i.e., $AUC_{incongruent} — AUC_{congruent}$) for each SOA and examined the impact of SOA on priming magnitude.

A two-way ANOVA (SOA × Cue) showed a significant main effect of SOA on priming magnitude (F (3, 174) = 4.73, MSE = 4253400.93, $p < 0.01$, partial $\eta^2 = 0.08$). Planned t-tests showed that the priming magnitude for 200ms SOA (M = 643.72, SD = 143.21) was significantly larger than that for 1000ms SOA (M = -137.26; SD = 154.32); $t(43) = 2.24$, $p = 0.03$.

There was no two-way interaction effect (SOA × Cue) on the priming magnitude ($F < 1$). Nevertheless, the impact of SOA was still reported separately for the cued and uncued conditions.

In the cued condition, a one-way ANOVA showed a significant difference of priming magnitudes among the four SOA conditions; F (3, 174) =5.59, MSE = 1284743.82, $p = 0.00$. Planned t-tests showed that the priming magnitude in the 200ms SOA condition was significantly larger than that in the 50ms and that in the 1000ms SOA condition. (Figure 24).

In the uncued condition, a one-way ANOVA showed no significant difference of priming magnitudes among four SOAs; F (3, 174) =1.92, MSE = 2703813.17, $p = 0.13$. It seems that the impact of SOA on priming magnitudes was mostly present in the cued condition, where subliminal semantic processing was assisted by top-down attention (Figure 24).

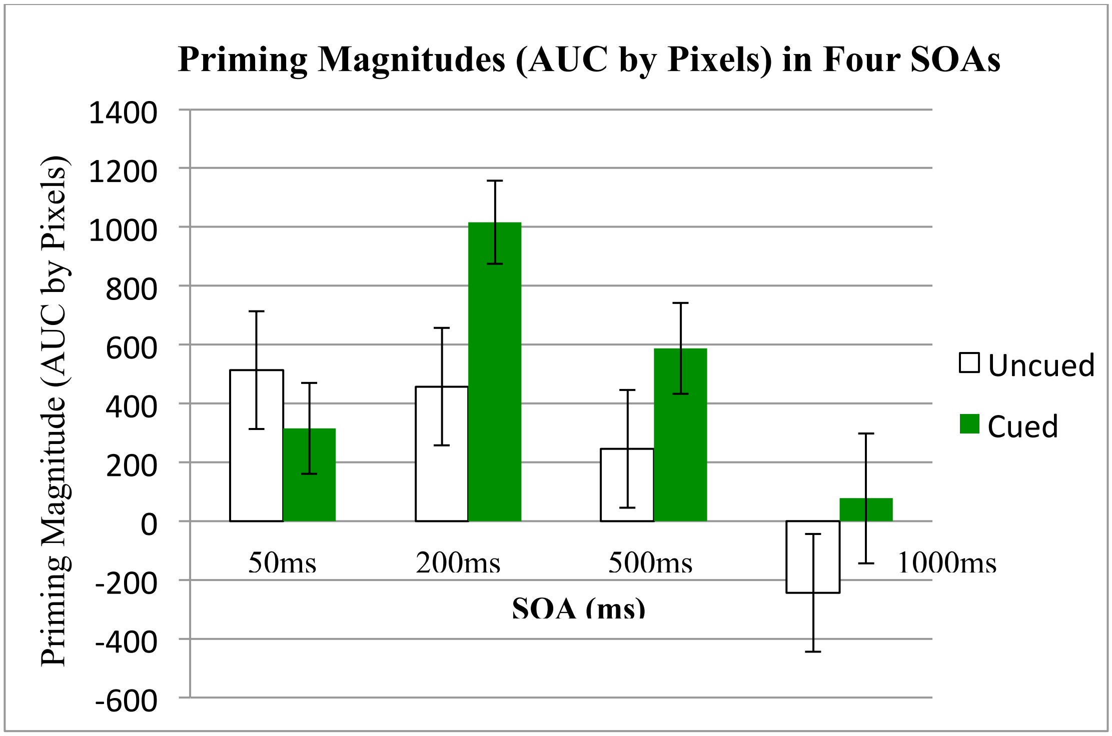


Figure 24. Priming magnitudes in four SOAs in cued and uncued conditions. The X-axis denotes the four SOA conditions, while the Y-axis is the amount of pixels. The error bars are two standard errors in length.

3.3.5.3 Impacts of top-down attention (cue) on congruency effects

The two-way ANOVA (cue × SOA) on the priming magnitude (i.e., AUC $_{incongruent}$ — AUC $_{congruent}$) showed a marginally significant main effect of cue (M_{cued} = 498.70, M_{uncued} = 242.80, $F(3, 174) = 4.73$, $MSE = 4253400.93$, $p < 0.01$, partial η^2 = 0.08). Comparing priming magnitudes (i.e., AUC $_{incongruent}$ — AUC $_{congruent}$) between the cue and uncued conditions for each SOA (Table 17), paired t-tests showed that in the 200ms SOA condition, the priming magnitude was significantly larger in the cued (M = 1015.93) than in the uncued conditions (M = 457.62); $t(44) = 2.06$, $p < 0.05$, Cohen's d =

0.62 (Table 17; Figure 25-28). No other comparisons between cued and uncued conditions reached the significant level.

Table 17 Comparing priming magnitudes between cued and uncued conditions

SOA	*N*	Cued	Uncued	*t*	*p*	Cohen's *d*
50	45	314.75	512.98	-0.57	0.57	0.17
200	45	1015.93	457.62	2.06	<0.05	0.62
500	45	586.77	245.16	1.29	0.20	0.39
1000	43	77.36	-244.57	1.21	0.23	0.37

Note. The priming magnitude is the AUC difference between congruent and incongruent trials (i.e., $AUC_{incongruent} — AUC_{congruent}$) and is measured by amounts of pixels.

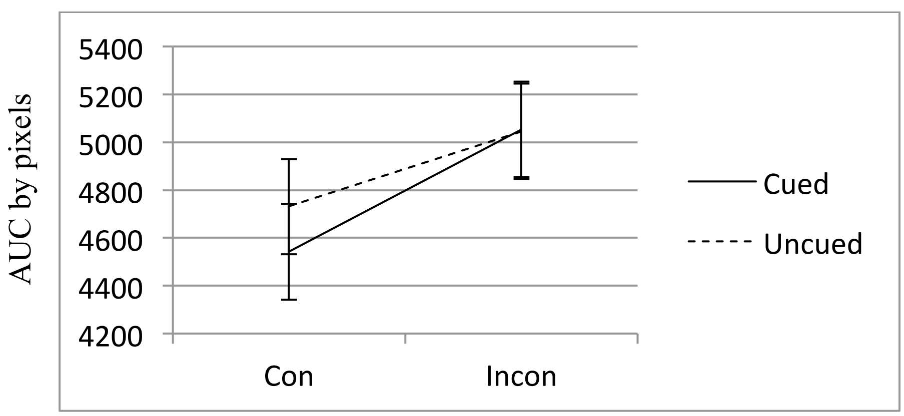


Figure 25. AUCs in the 50ms SOA condition. The AUC is measured by amounts of pixels. The error bars are two standard errors in length.

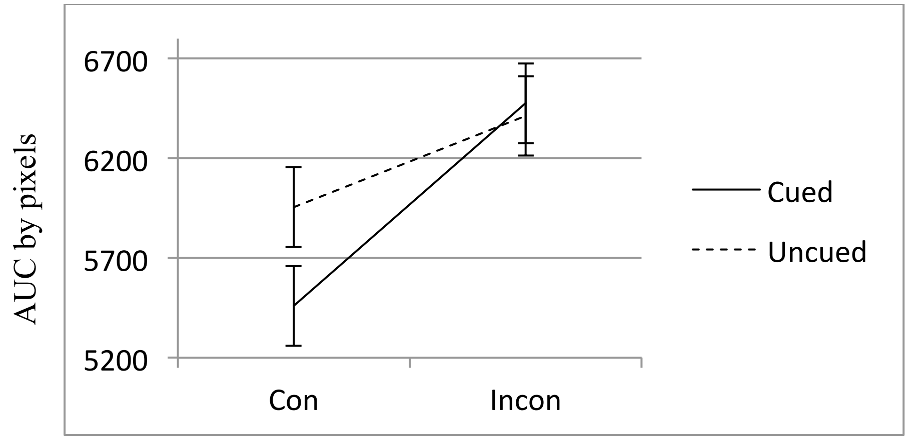


Figure 26. AUCs in the 200ms SOA condition. The AUC is measured by amounts of pixels. The error bars are two standard errors in length. Title, units, labels

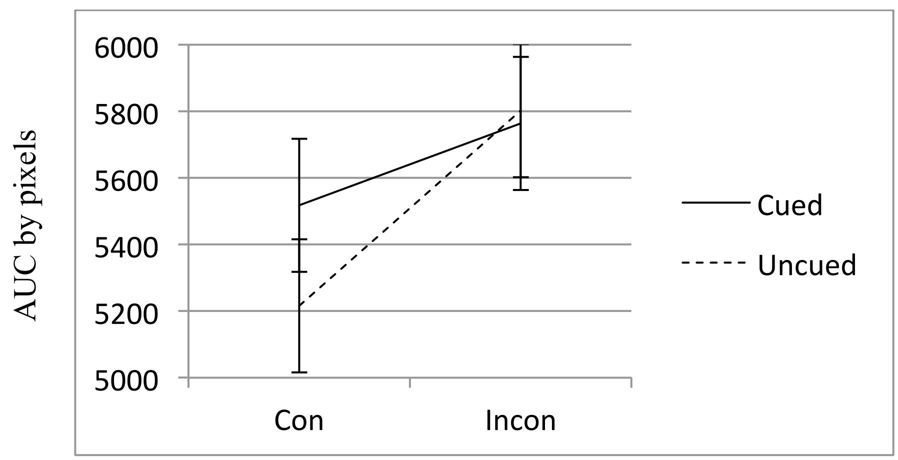


Figure 27. AUCs in the 500ms SOA condition. The AUC is measured by amounts of pixels. The error bars are two standard errors in length. Title, units, labels

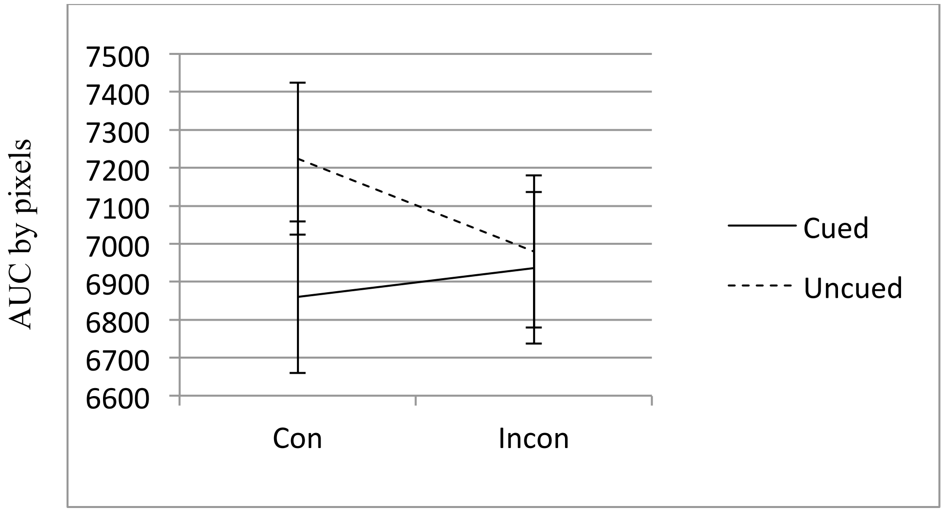


Figure 28. AUCs in the 1000ms SOA condition. The AUC is measured by amounts of pixels. The error bars are two standard errors in length. Title, units, labels.

3.3.5.4 Awareness analysis

In the awareness test, the *d'*s were not significantly different from zero: in the 50ms condition, $M = 0.001$, $t(44) = 0.15$, $p = 0.88$; in the 200ms condition, $M = -0.001$, $t(44) = 0.07$, $p = 0.94$; in the 500ms condition, $M < 0.001$, $t(44) = 0.44$, $p > 0.95$; in the 1000ms condition, $M = -0.004$, $t(42) = -0.46$, $p > 0.90$. Thus, participants could hardly see the masked primes. A one-way ANOVA showed no difference of *d'*s among the four SOAs ($F < 1.00$), suggesting that SOA did not influence participants' awareness of the masked primes.

Linear regressions with priming magnitudes (i.e., $AUC_{incongruent} — AUC_{congruent}$) showed no correlation between the priming magnitudes and *d'*s in neither cued nor uncued conditions, suggesting that the observed congruency effects were not influenced by participants' awareness of masked primes (Table 18 & 19). Meanwhile, the regressions revealed significant intercepts at null *d'* in the 200ms and 500ms SOA conditions in the cued condition, and in the 200ms SOA condition in the uncued condition, suggesting that in these conditions, the subliminal semantic priming was still significant for participants who could hardly see the masked primes, (Table 18 & 19; Figure 29).

Table 18 Regressions with priming magnitudes on *d*'s in the cued condition

SOA		*B*	*t*	*p*
50ms	*constant*	311.61	2.00	0.052
	d'	0.14	0.91	0.37
200ms	*constant*	1014.87	7.12	<0.001
	d'	-0.10	-0.67	0.50
500ms	*constant*	586.79	3.74	0.001
	d'	-0.04	-0.24	0.81
1000ms	*constant*	62.32	0.28	0.78
	d'	-0.15	-0.95	0.35

Note. The priming magnitude is calculated by $AUC_{incongruent}$ — $AUC_{congruent}$.

Table 19 Regressions with priming magnitudes on *d*'s in the uncued condition

SOA		*B*	*t*	*p*
50ms	*constant*	510.08	1.71	0.10
	d'	0.07	0.44	0.66
200ms	*constant*	460.35	2.11	0.04
	d'	0.17	1.14	0.26
500ms	*constant*	245.03	0.96	0.34
	d'	0.13	0.85	0.40
1000ms	*constant*	-247.38	-1.21	0.23
	d'	-0.03	-0.19	0.85

Note. The priming magnitude is calculated by $AUC_{incongruent} — AUC_{congruent}$.

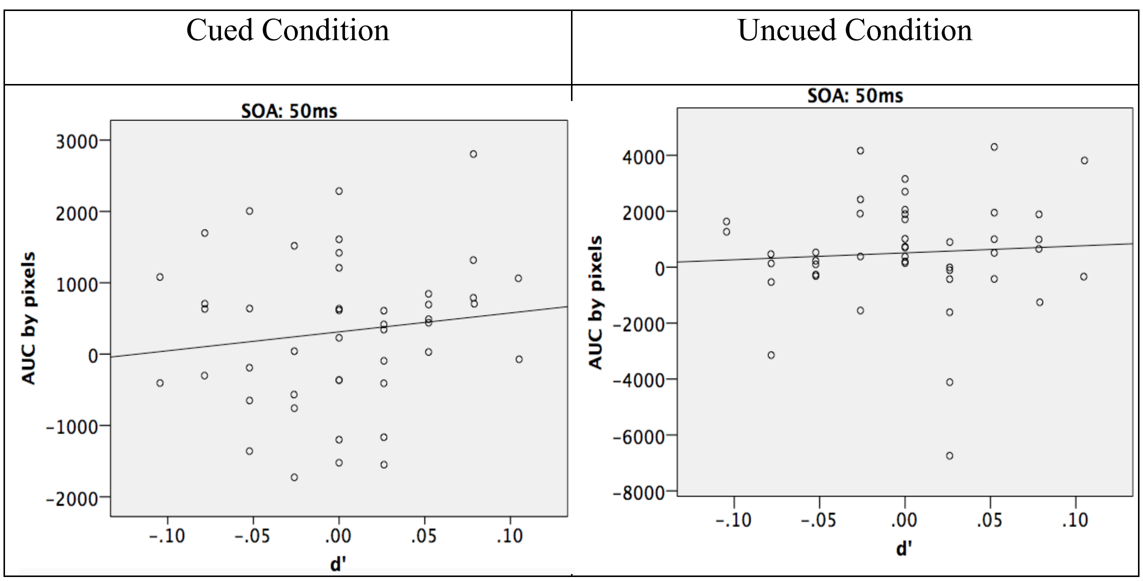


Figure 29. Linear regressions with priming magnitudes on *d'*s by SOAs.

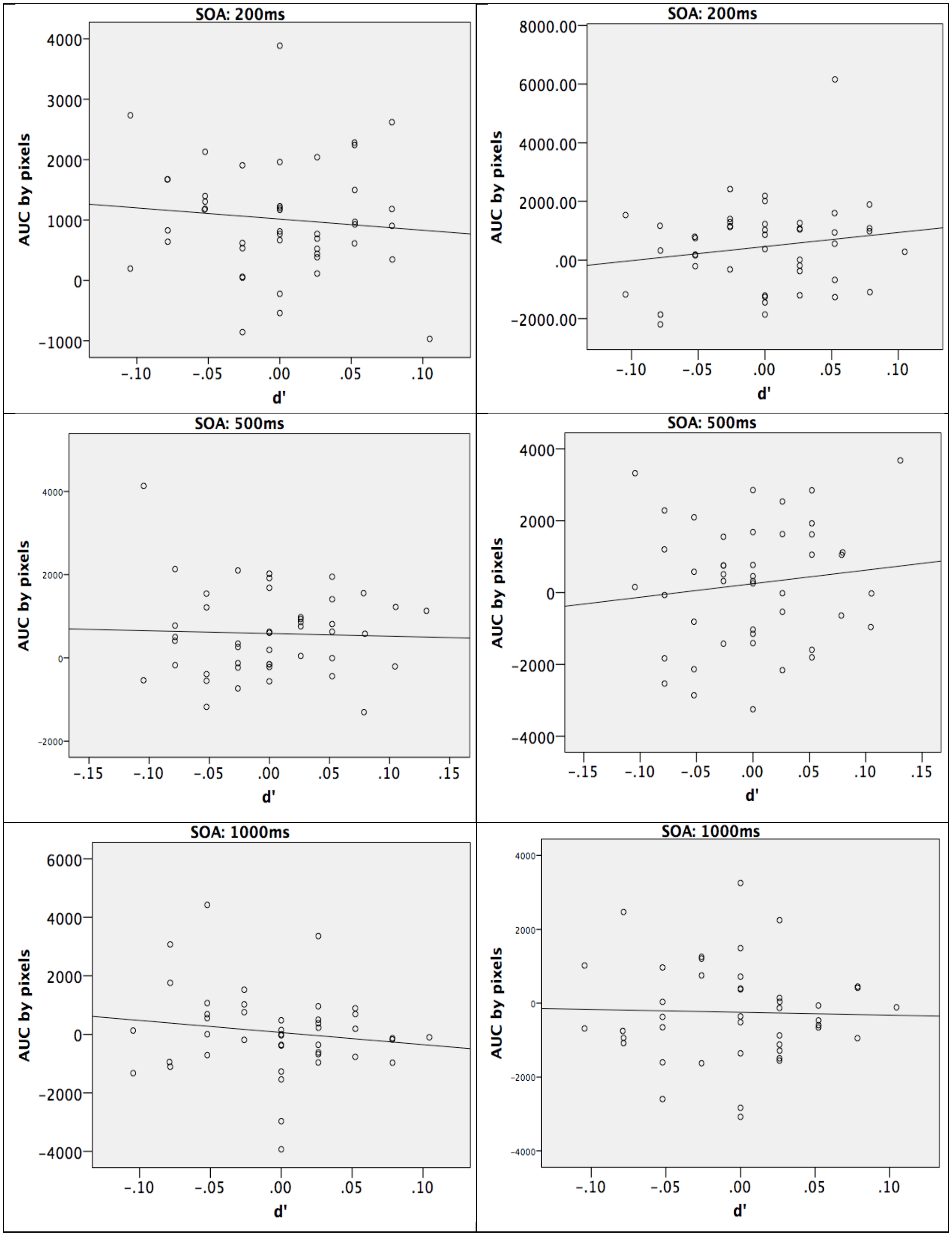


Figure 29 Continued.

T-test comparing the mean response bias to one suggested that participants were slightly biased towards the “Large” response in the awareness test: in the 50ms condition, $M = 0.983$, $t(44) = 1.82$, $p = 0.08$; in the 200ms condition, $M = 0.976$, $t(44) = 2.37$, $p = 0.02$; in the 500ms condition, $M = 0.981$, $t(44) = 2.20$, $p = 0.03$; in the 1000ms condition, $M = 0.991$, $t(42) = 1.01$, $p = 0.32$.

3.3.6 Discussion

Experiment 5 is to clarify how exactly top-down attention influences subliminal semantic processing by examining the time course of priming. The impact of SOAs is prominent in the cued condition, where subliminal semantic processing was strengthened by top-down attention; priming effects were significant when the SOA was in a moderate range (e.g., 200ms, 500ms). In the 50ms and 500ms SOA conditions, the priming was significant in the cued condition while absent in the uncued condition, suggesting that the lifespan of subliminal semantic processing could be extended by top-down attention. In addition, in the 200ms SOA condition, the amplification effect of top-down attention was significant.

Taking Experiments 3-5 together, subliminal semantic processing seems to arrive at its peak at around 200ms after the onset of primes, which corresponds to the N200 components reported in previous EEG research (Sergent, Baillet, & Dehaene, 2005). Although it appears that top-down attention extended the lifespan of subliminal semantic processing from 200ms SOA to 50ms SOA and 500ms SOA, such an extension effect is possibly a byproduct resulting from the amplification of top-down attention. Based on the current results, it is difficult to decide whether the extension effect is caused by the amplification effect, or these two effects are parallel and independent of each other.

The pattern of results found in Experiments 3 & 4 that presenting a green cue selectively impeded responses to incongruent trials was not replicated in Experiment 5. This inconsistence can be explained by different SOAs: the SOA was 100ms in Experiments 3 & 4 while 50ms, 200ms, 500ms, or 1000ms in Experiment 5. It is also possible that this pattern per se is not reliable, given that different cue colors elicited different patterns of results in Experiment 4. Whether the green color selectively polarizes semantic conflicts between primes and targets needs future clarification.

It is interesting that the lifespan of temporal attention window is longer than 1000ms, rather than a few hundreds of milliseconds suggested by Naccache et al. (2002). This is because semantic priming was significant in the cued condition while absent in the uncued condition for the 500ms SOA; without assistance of top-down attention, subliminal semantic processing disappeared when the SOA was as long as 500ms. In other words, to sustain subliminal semantic processing, the temporal attention window should remain open for at least 500ms after the onset of primes. Given that the onset of the cue was 484ms prior to the onset of the prime (i.e., 200ms for the cue and 284ms for the pre-mask), the temporal attention window remained open for at least 1000ms to elicit priming (i.e., 200ms cue + 284ms pre-mask + 500ms SOA + some response latency).

Although 200ms SOA elicited largest priming effects in Experiment 5, 200ms is not necessarily the best SOA for semantic priming. Other studies show that the time course of masked priming depends on tasks. For example, in Experiment 6 in the Fowler et al. (1981) study, participants judged whether a target word was previously presented, and masked semantic priming was absent for 200ms SOA but significant for 2000ms SOA. It is noteworthy that the duration of each trial was fixed in this experiment; thus, it can be inferred that in this case, the temporal attention window was not open until after 200ms whereas lasted for more than 2000ms. The inconsistent time courses of semantic priming in different tasks can be attributed to the difficulty of tasks. Because the word detection task is easier than the numeric judgment task, the semantic impact of masked primes can stay longer in the word detection task without being disrupted by effortful numeric judgment.

Other evidence shows different time courses of masked priming. For example, in a "same / different" judgment task, semantic priming was absent when the SOA was as short as 316ms (Opstal et al., 2010); in a spatial detection task (Chou & Yeh, 2011), 100ms SOA and 1000ms SOA elicited opposite priming effects. Obviously, the time course of priming depends on specific tasks and stimuli, because the underlying cognitive processes are different.

In summary, top-down attention is likely to extend the lifespan and amplify the magnitude of subliminal semantic processing. The temporal attention window (TAW) could last for more than 1000ms.

CHAPTER IV

SUMMARY AND CONCLUSIONS

4.1 Summary of the Five Experiments

Unlike the traditional view that unconscious cognition is stereotypical and independent of cognitive control, recent evidence shows that subliminal processing can be elaborate and flexible. In an attempt to clarify the interaction between cognitive control and subliminal processing, I apply cursor motion measure to investigate the role of top-down attention in elaborate subliminal priming.

Experiment 1 examined the efficacy of the cursor motion measure for elaborate semantic processing. To minimize the potential contamination from perceptual priming, the prime-target relation was made indirect; larger congruency effects were found for the AUC measure than the response time measure. In Experiment 2, effect sizes of masked semantic priming were directly compared between the AUC and RT measures; consistent with Experiment 1, the AUC measure revealed larger effect size than the RT measure, suggesting that the cursor motion analysis is more sensitive than the RT analysis for masked semantic priming.

Armed with this methodological advantage, I investigated the role of top-down attention in subliminal semantic processing in Experiments 3-5. In Experiment 3, cursor motion method was applied to the numeric comparison task used by Naccache et al. (2002) study. By contrasting cued and uncued conditions, I examined whether the assistance from top-down attention was *necessary* for subliminal semantic priming.

Consistent with the Naccache et al. (2002) study, top-down attention amplified subliminal semantic processing; however, masked semantic priming was still significant with little assistance from top-down attention. These results imply that top-down attention may not be necessary for elaborate subliminal processing. Experiment 4 further examined whether the color of cues influences semantic priming, and found that the effect of colors was overridden by the effect of semantic congruency and top-down attention. Experiment 5 investigated how top-down attention influences subliminal semantic processing by looking at the time course of priming, and found that top-down attention extends the lifespan and amplifies the magnitude of subliminal semantic processing, suggesting that the temporal attention window remains open for more than 1000ms.

Taken together, the five experiments suggest that subliminal semantic processing can be reliably measured by the cursor motion measure. Top-down attention extends the lifespan and amplifies the magnitude of subliminal semantic processing; attention, however, is not as essential as suggested by the theory of temporal attention window and global workspace because elaborate subliminal processing occurs spontaneously with little assistance from top-down attention.

4.2 Theoretical Implications

The theory of temporal attention window and global workspace explains how cognitive control and subliminal processing interacted (Baars, 1988; Dehaene et al., 1998; 2006). On the other hand, evidence for elaborate subliminal processing is limited, and effects of masked priming measured by response times are often small and difficult to be replicated (Van den Bussche, Van den Noortgate, & Reynvoet, 2009).

Applying the cursor motion method to masked semantic priming studies, this dissertation sheds light on how top-down attention influences subliminal semantic processing. Naccache et al. (2002) find no congruency effects in near absence of attention, and argue for the necessity of attention in elaborate subliminal processing. However, Experiments 3-5 demonstrate the presence of subliminal semantic priming with little assistance from top-down attention. Thus, the absence of priming in the uncued condition in the Naccache et al. (2002) study can be attributed to the lack of sensitivity of response times.

The classic view is that conscious and unconscious processing is distinct. First, consciousness and attention are considered to be the same: being conscious of something means attending to it, and vice versa. Conscious processing is controlled by attention, which selectively suppresses irrelevant processing to optimize the processing of limited information. In contrast, subliminal processing is diffuse, parallel, and free from cognitive control. This view is supported by evidence of top-down selection and bottom–up capture (Posner & Dehaene, 1994; Posner & Fan, 2008). Second, the involvement of awareness can impede subliminal processing because attention selectively suppresses autonomous processing; therefore, consciousness tends to restrict rather than assist subliminal processing (Anderson, 1983; Collins & Loftus, 1975; Dixon, 1971; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

Nevertheless, recent evidence highlights the distinction between consciousness and attention: consciousness is subjective experience while attention is the mechanism allocating limited cognitive resource (Koch & Tsuchiya, 2007). The relationships between attention and consciousness can be classified into four categories: consciousness with attention, no consciousness without attention, attention without consciousness, consciousness without attention (Koch, & Tsuchiya, 2007; Cohen, Cavanagh, Chun, & Nakayama, 2012). Previous evidence demonstrates that attention to invisible stimuli influences subliminal processing. This dissertation adds further evidence to the robustness of elaborate subliminal processing with little help of attention. On the other hand, there is little evidence for consciousness without attention (Cohen et al., 2012). In brief, attention influences both conscious and unconscious processing, and is necessary for consciousness while unnecessary for unconscious processing.

More importantly, the elaborate and flexible nature of subliminal processing revealed by recent research makes the boundary between conscious and unconscious processing vague (Dehaene et al., 2006; Spruyt et al., 2009; 2012). Consistent with these findings, Experiments 3-5 show that top-down attention amplifies the magnitude and extends the lifespan of subliminal semantic processing. The theory of global workspace articulates the mechanism underlying the interplay of cognitive control and subliminal processing; the attention system in the global workspace selectively polarizes some while suppresses other processing by allocation limited cognitive resource (Dehaene et al., 1998; 2005). However, their argument for the necessity of attention is challenged by counterevidence for elaborate subliminal processing in near absence of attention. As suggested by Experiment 3-5, unattended semantic processing spontaneously lasts for a considerable lifespan rather than immediately fades away.

Given the link between cognitive control and subliminal processing, the dichotomous view that consciousness and unconsciousness are distinct seems outdated. Unconscious processing can be elaborate and flexible. States of consciousness are more likely on a continuum, with full consciousness at one end and unconsciousness (e.g., sleep, coma) at the other end (Dixion, 1971; Kihlstrom, 1993; Fish & Haase, 2011).

4.3 Limitations

Note that uncued and cued conditions do not perfectly correspond to actual states of attention: in the uncued condition, disrupted attention does not guarantee no attention at all; while presenting a visual cue to facilitate the attention does not mean that attention is fully deployed. Thus, we can only infer the role of attention. Because semantic priming was observed in both cued and uncued conditions consistently, assistance from top-down attention is more likely not mandate; masked primes is processed at a semantic level in near absence of attention, although attention does help priming.

Another issue is the assessment of awareness. Since subjective reports of awareness are inaccurate and unreliable, most masked priming studies apply an objective assessment of awareness developed by Draine and Greenwald (1998), which employs *d'* instead of raw accuracy to assess awareness. The *d'* can balance the response bias of individuals and is also more rigorous than the raw accuracy in awareness assessment. For example, a very low group accuracy of 0.52, which was close to the chance level, results in a group *d'* significantly higher than zero (Van Opstal et al., 2010). Generally speaking, the awareness test is conservative and tends to overestimate the prime visibility, because participants focus on masked primes in the awareness test while ignoring primes in the major judgment task. Admittedly, a null group *d'* does not guarantee that masked primes are invisible to all participants; some individuals are better than others at detecting briefly displayed stimuli, and merely perceptual registration can contribute to priming effects.

4.4 Future Directions

There are two types of top-down attention that can modulate subliminal processing: temporal attention and feature-specific attention (Dehaene et al., 2006; Koch et al., 2007). In this dissertation, only the temporal attention is investigated. It will be interesting to examine whether feature-specific attention influences subliminal semantic processing in a different manner. Although previous studied showed that subliminal semantic processing did not occur without assistance from feature-specific attention (Spruyt, et al., 2009; 2012), it is possible to challenge the necessity of feature-specific attention by replacing their response time measure with the cursor motion measures such as AUCs.

Although previous evidence and the present results suggest that elaborate subliminal processing occurs in near absence of attention, it is difficult to conclude that attention is not necessary at all because the experimental procedures do not eliminate attention completely. More rigorous experimental paradigms, such as attentional blink and inattentional blindness, are needed in the future to add further evidence to the attention-consciousness relationship (Cohen et al., 2012).

4.5 Conclusions

This dissertation employs a cursor motion method to investigate the role of top-down attention in elaborate subliminal processing. The cursor motion method serves as a reliable tool to assess masked semantic priming, and dynamic temporal-spatial measures such as the AUC are more sensitive than temporal data. Top-down attention helps subliminal semantic processing, but is not as essential as suggested by the theory of temporal attention window and global workspace. The cue color may influence priming to some extent, but the effect of cue colors on congruency effect is limited, compared to the effects of semantic congruency and top-down attention. The temporal attention window (TAW) extends the lifespan and amplifies the magnitude of subliminal semantic processing, and lasts for at least 1000ms.

REFERENCES

Abrams, R. L., & Greenwald, A. G. (2000). Parts outweigh the whole (word) in unconscious analysis of meaning. *Psychological Science*, *11*(2), 118-124.

Abrams, R. L., Klinger, M. R., & Greenwald, A. G. (2002). Subliminal words activate semantic categories (not automated motor responses). *Psychonomic Bulletin & Review*, *9*(1), 100-106.

Aglioti, S., DeSouza, J. F., & Goodale, M. A. (1995). Size-contrast illusions deceive the eye but not the hand. *Current biology*, *5*(6), 679-685.

Amihai, I., Deouell, L., & Bentin, S. (2011). Conscious awareness is necessary for processing race and gender information from faces. *Consciousness and cognition*, *20*(2), 269-279.

Anderson, J. R. (1983). A spreading activation theory of memory. *Journal of verbal learning and verbal behavior*, *22*(3), 261-295.

Baars, B.J. (1989). A Cognitive Theory of Consciousness (Cambridge, Mass: Cambridge University Press).

Boulenger, V., Roy, A., Paulignan, Y., Deprez, V., Jeannerod, M., & Nazir, T. (2006). Cross-talk between language processes and overt motor behavior in the first 200 msec of processing. *Cognitive Neuroscience, Journal of*, *18*(10), 1607-1615.

Bowman, C., Yamauchi, T., & Xiao, K. (2015). Emotion, voices and musical instruments: Repeated exposure to angry vocal sounds makes instrumental sounds angrier. *2015 International Conference on Affective Computing and Intelligent Interaction* (ACII). pp. 670-675. IEEE Computer Society.

Chapman, C. S., Gallivan, J. P., Wood, D. K., Milne, J. L., Culham, J. C., & Goodale, M. A. (2010). Reaching for the unknown: multiple target encoding and real-time decision-making in a rapid reach task. *Cognition*, *116*(2), 168-176.

Chou, W. L., & Yeh, S. L. (2011). Subliminal spatial cues capture attention and strengthen between-object link. *Consciousness and cognition*, *20*(4), 1265-1271.

Cohen, M. A., Alvarez, G. A., & Nakayama, K. (2011). Natural-scene perception requires attention. *Psychological science*.

Cohen, M. A., Cavanagh, P., Chun, M. M., & Nakayama, K. (2012). The attentional requirements of consciousness. *Trends in cognitive sciences*, *16*(8), 411-417.

Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological review*, *82*(6), 407.

Dale, R., Kehoe, C., & Spivey, M. J. (2007). Graded motor responses in the time course of categorizing atypical exemplars. *Memory & Cognition*, *35*(1), 15-28.

Damian, M. F. (2001). Congruity effects evoked by subliminally presented primes: automaticity rather than semantic processing. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 154.

De Gardelle, V., Charles, L., & Kouider, S. (2011). Perceptual awareness and categorical representation of faces: Evidence from masked priming. *Consciousness and cognition*, *20*(4), 1272-1281.

Dehaene, S., & Changeux, J. P. (2011). Experimental and theoretical approaches to conscious processing. *Neuron*, *70*(2), 200-227.

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: a testable taxonomy. *Trends in cognitive sciences*, *10*(5), 204-211.

Dehaene, S., Kerszberg, M., & Changeux, J. P. (1998). A neuronal model of a global workspace in effortful cognitive tasks. *Proceedings of the National Academy of Sciences*, *95*(24), 14529-14534.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. *Cognition*, *79*(1), 1-37.

Dehaene, S., Naccache, L., Le Clec'H, G., Koechlin, E., Mueller, M., Dehaene-Lambertz, G., ... & Le Bihan, D. (1998). Imaging unconscious semantic priming. *Nature*, *395*(6702), 597-600.

Dell'Acqua, R., & Grainger, J. (1999). Unconscious semantic priming from pictures. *Cognition*, *73*(1), B1-B15.

Desender, K., & Van den Bussche, E. (2012). Is consciousness necessary for conflict adaptation? A state of the art. *Frontiers in Human Neuroscience*, *6*(3), 1-13.

Dixon, N. F. (1971). Subliminal perception: The nature of a controversy. Maidenhead, Berkshire, England: McGraw-Hill Publishing Company Limited.

Draine, S. C., & Greenwald, A. G. (1998). Replicable unconscious semantic priming. *Journal of Experimental Psychology: General*, *127*(3), 286.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(4), 380-390.

Faulkenberry, T. J. (2014). Hand movements reflect competitive processing in numerical cognition. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *68*(3), 147.

Faulkenberry, T. J., & Rey, A. E. (2014). Extending the reach of mousetracking in numerical cognition: a comment on Fischer and Hartmann (2014). *Frontiers in psychology*, *5*.

Febrero-Bande, M., & de la Fuente, M. O. (2012). Statistical computing in functional data analysis: The R Package fda.usc, Journal of Statistical Software, 51 (4), 1-28.

Finkbeiner, M., & Friedman, J. (2011). The flexibility of nonconsciously deployed cognitive processes: evidence from masked congruence priming. *PloS one*, *6*(2), e17095.

Fisk, G. D., & Haase, S. J. (2011). The relationship between the objective identification threshold and priming effects does not provide a definitive boundary between conscious and unconscious perceptual processes. *Consciousness and cognition*, *20*(4), 1221-1231.

Fowler, C. A., Wolford, G., Slade, R., & Tassinary, L. (1981). Lexical access with and without awareness. *Journal of Experimental Psychology: General*, *110*(3), 341.

Freeman, J. B., & Ambady, N. (2010). MouseTracker: Software for studying real-time mental processing using a computer mouse-tracking method. *Behavior Research Methods*, *42*(1), 226-241.

Freeman, J. B., & Ambady, N. (2011). A dynamic interactive theory of person construal. *Psychological review*, *118*(2), 247.

Freeman, J. B., Ambady, N., Rule, N. O., & Johnson, K. L. (2008). Will a category cue attract you? Motor output reveals dynamic competition across person construal. *Journal of Experimental Psychology: General*, *137*(4), 673.

Freeman, J. B., Johnson, K. L., Ambady, N., & Rule, N. O. (2010). Sexual orientation perception involves gendered facial cues. *Personality and Social Psychology Bulletin*.

Freeman, J. B., Pauker, K., Apfelbaum, E. P., & Ambady, N. (2010). Continuous dynamics in the real-time perception of race. *Journal of Experimental Social Psychology*, *46*(1), 179-185.

Friedman, J., & Finkbeiner, M. (2010). Temporal dynamics of masked congruence priming: evidence from reaching trajectories.

Fritz, C., Morris, P. E., & Richler, J. J. (2012). Effect size estimates: current use, calculations, and interpretation. *Journal of Experimental Psychology: General*, *141*(1), 2-18.

Gallivan, J. P. & Chapman, C. S. (2014). Three-dimensional reach trajectories as a probe of real-time decision-making between multiple competing targets. Frontiers in Neuroscience, 8, 1-19.

Ganor-Stern, D., & Goldman, R. (2015). Reaching towards an end: Numerical end and distance effects in motor movements. *Journal of Cognitive Psychology*, *27*(4), 490-498.

Gobbini, M. I., Gors, J. D., Halchenko, Y. O., Rogers, C., Guntupalli, J. S., Hughes, H., & Cipolli, C. (2013). Prioritized detection of personally familiar faces. *PLoS One*, *8*(6), e66620.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: strategic control of activation of responses. *Journal of Experimental Psychology: General*, *121*(4), 480-506.

Greenwald, A. G., Draine, S. C., & Abrams, R. L. (1996). Three cognitive markers of unconscious semantic activation. *Science*, *273*(5282), 1699-1702.

Heinemann, A., Kunde, W., & Kiesel, A. (2009). Context-specific prime-congruency effects: On the role of conscious stimulus representations for cognitive control. *Consciousness and cognition*, *18*(4), 966-976.

Hsieh, P. J., Colas, J. T., & Kanwisher, N. (2011). Pop-out without awareness unseen feature singletons capture attention only when top-down attention is available. *Psychological science*, *22*(9), 1220-1226.

Kiefer, M., & Martens, U. (2010). Attentional sensitization of unconscious cognition: task sets modulate subsequent masked semantic priming. *Journal of Experimental Psychology: General*, *139*(3), 464.

Kiesel, A., Kunde, W., Pohl, C., Berner, M. P., & Hoffmann, J. (2009). Playing chess unconsciously. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(1), 292.

Kihlstrom, J. F. (1993). The continuum of consciousness. *Consciousness and Cognition*, *2*(4), 334-354.

Kinoshita, S., Forster, K. I., & Mozer, M. C. (2008). Unconscious cognition isn't that smart: Modulation of masked repetition priming effect in the word naming task. *Cognition*, *107*(2), 623-649.

Klauer, K. C., Eder, A. B., Greenwald, A. G., & Abrams, R. L. (2007). Priming of semantic classifications by novel subliminal prime words. *Consciousness and Cognition*, *16*(1), 63-83.

Koch, C., & Crick, F. (2001). The zombie within. *Nature*, *411*(6840), 893-893.

Koechlin, E., Naccache, L., Block, E., & Dehaene, S. (1999). Primed numbers: exploring the modularity of numerical representations with masked and unmasked semantic priming. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1882.

Kouider, S., & Dehaene, S. (2007). Levels of processing during non-conscious perception: a critical review of visual masking. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *362*(1481), 857-875.

Kunde, W., Kiesel, A., & Hoffmann, J. (2003). Conscious control over the content of unconscious cognition. *Cognition*, *88*(2), 223-242.

Li, F. F., VanRullen, R., Koch, C., & Perona, P. (2002). Rapid natural scene categorization in the near absence of attention. *Proceedings of the National Academy of Sciences*, *99*(14), 9596-9601.

Macmillan, N. A., & Creelman, C. D. (1996). Triangles in ROC space: History and theory of "nonparametric" measures of sensitivity and response bias. *Psychonomic Bulletin & Review*, *3*(2), 164-170.

Marcel, A. J. (1983). Conscious and unconscious perception: Experiments on visual masking and word recognition. *Cognitive psychology*, *15*(2), 197-237.

McKinstry, C., Dale, R., & Spivey, M. J. (2008). Action dynamics reveal parallel competition in decision making. *Psychological Science*, *19*(1), 22-24.

Meyer, D. E., & Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: evidence of a dependence between retrieval operations. *Journal of experimental psychology*, *90*(2), 227.

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action* (Vol. 27).

Naccache, L., Blandin, E., & Dehaene, S. (2002). Unconscious masked priming depends on temporal attention. *Psychological Science*, *13*(5), 416-424.

Naccache, L., & Dehaene, S. (2001). Unconscious semantic priming extends to novel unseen stimuli. *Cognition*, *80*(3), 215-229.

Norman, D.A., and Shallice, T. (1980). Attention to action: Willed and automatic control of behavior. In Consciousness and Self-Regulation, R.J. Davidson, G.E. Schwartz, and D. Shapiro, eds. (New York: Plenum Press), pp. 1–18.

Ortells, J. J., Marí-Beffa, P., & Plaza-Ayllón, V. (2013). Unconscious congruency priming from unpracticed words is modulated by prime–target semantic relatedness. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(2), 394.

Posner, M. I., & Dehaene, S. (1994). Attentional networks. *Trends in neurosciences*, *17*(2), 75-79.

Posner, M. I., & Fan, J. (2008). Attention as an organ system. *Topics in integrative neuroscience*, 31-61.

Proctor, R. W. (1981). A unified theory for matching-task phenomena. *Psychological Review*, *88*(4), 291.

Rahnev, D. A., Huang, E., & Lau, H. (2012). Subliminal stimuli in the near absence of attention influence top-down cognitive control. *Attention, Perception, & Psychophysics*, *74*(3), 521-532.

Ratcliff, R. (1985). Theoretical interpretations of the speed and accuracy of positive and negative responses. *Psychological review*, *92*(2), 212.

Ratcliff, R. (1987). More on the speed and accuracy of positive and negative responses.

Reddy, L., Wilken, P., & Koch, C. (2004). Face-gender discrimination is possible in the near-absence of attention. *Journal of Vision*, *4*(2), 4.

Rosnow, R. L., & Rosenthal, R. (1991). If you're looking at the cell means, you're not looking at only the interaction (unless all main effects are zero).

Santens, S., Goossens, S., & Verguts, T. (2011). Distance in motion: response trajectories reveal the dynamics of number comparison. *PloS one*, *6*, e25429.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological review*, *84*(1), 1.

Schoups, A. A., Vogels, R., & Orban, G. A. (1995). Human perceptual learning in identifying the oblique orientation: retinotopy, orientation specificity and monocularity. *The Journal of physiology*, *483*(Pt 3), 797-810.

Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature neuroscience*, *8*(10), 1391-1400.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological review*, *84*(2), 127.

Song, J. H., & Nakayama, K. (2009). Hidden cognitive states revealed in choice reaching tasks. *Trends in cognitive sciences*, *13*(8), 360-366.

Spivey, M. J., & Dale, R. (2006). Continuous dynamics in real-time cognition. *Current Directions in Psychological Science*, *15*(5), 207-211.

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(29), 10393-10398.

Spruyt, A., De Houwer, J., Everaert, T., & Hermans, D. (2012). Unconscious semantic activation depends on feature-specific attention allocation. *Cognition*, *122*(1), 91-95.

Spruyt, A., De Houwer, J., & Hermans, D. (2009). Modulation of semantic priming by feature-specific attention allocation.

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior research methods, instruments, & computers*, *31*(1), 137-149.

Tassinary, L. G., Orr, S. P., Wolford, G., Napps, S. E., & Lanzetta, J. T. (1984). The role of awareness in affective information processing: An exploration of the Zajonc hypothesis. *Bulletin of the Psychonomic Society*, *22*(6), 489-492.

Van den Bussche, E., Notebaert, K., & Reynvoet, B. (2009). Masked primes can be genuinely semantically processed: A picture prime study. *Experimental psychology*, *56*(5), 295-300.

Van den Bussche, E., Van den Noortgate, W., & Reynvoet, B. (2009). Mechanisms of masked priming: a meta-analysis. *Psychological bulletin*, *135*(3), 452.

Van Gaal, S., Naccache, L., Meuwese, J. D., van Loon, A. M., Leighton, A. H., Cohen, L., & Dehaene, S. (2014). Can the meaning of multiple words be integrated unconsciously?. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *369*(1641), 20130212.

Van Opstal, F., Calderon, C. B., Gevers, W., & Verguts, T. (2011). Setting the stage subliminally: unconscious context effects. *Consciousness and cognition*, *20*(4), 1860-1864.

Van Opstal, F., de Lange, F. P., & Dehaene, S. (2011). Rapid parallel semantic processing of numbers without awareness. *Cognition*, *120*(1), 136-147.

Van Opstal, F., Gevers, W., Osman, M., & Verguts, T. (2010). Unconscious task application. *Consciousness and cognition*, *19*(4), 999-1006.

Van Opstal, F., Moors, A., Fias, W., & Verguts, T. (2008). Offline and online automatic number comparison. *Psychological research*, *72*(3), 347-352.

Van Opstal, F., Reynvoet, B., & Verguts, T. (2005). Unconscious semantic categorization and mask interactions: An elaborate response to Kunde et al.(2005). *Cognition*, *97*(1), 107-113.

Verguts, T., & Van Opstal, F. (2005). Dissociation of the distance effect and size effect in one-digit numbers. *Psychonomic Bulletin & Review*, *12*(5), 925-930.

Weibel, S., Giersch, A., Dehaene, S., & Huron, C. (2013). Unconscious task set priming with phonological and semantic tasks. *Consciousness and cognition*, *22*(2), 517-527.

Xiao, K., & Yamauchi, T. (2014). Semantic priming revealed by cursor motion trajectories. *Consciousness and cognition*, *27*, 42-52.

Xiao, K., Yamauchi, T. (2015). Subliminal Semantic Priming in Near Absence of Attention: a Cursor Motion Study. *Consciousness and Cognition,* 38, 88-98.

Xiao, K., Yamauchi, T., & Bowman, C. (2015). Assessing masked semantic priming: Cursor trajectory versus response Time. In D. C. Noelle, R. Dale, A. S. Warlaumont, J. Yoshimi, T. Matlock, C. D. Jennings, & P. P. Maglio (Eds.), Proceedings of the 37th Annual Conference of the Cognitive Science Society (pp. 2691-2696). Austin, TX: Cognitive Science Society.

Yamauchi, T. (2013). Mouse trajectories and state anxiety: feature selection with random forest. In *Affective Computing and Intelligent Interaction (ACII), 2013 Humaine Association Conference on* (pp. 399-404). IEEE.

Yamauchi, T., & Bowman, C. (2014). Mining Cursor Motions to Find the Gender, Experience, and Feelings of Computer Users. In *Data Mining Workshop (ICDMW), 2014 IEEE International Conference on* (pp. 221-230). IEEE Computer Society.

Yamauchi, T., Kohn, N., & Yu, N. Y. (2007). Tracking cursor motion in feature inference: Category labels are different from feature labels. *Memory & Cognition*, *35*(5), 852-863.

Yamauchi, T., Seo, J. H., Choe, Y., Bowman, C., & Xiao, K. (2015). Assessing emotions by cursor motions: An affective computing approach. In D. C. Noelle, R. Dale, A. S. Warlaumont, J. Yoshimi, T. Matlock, C. D. Jennings, & P. P. Maglio

(Eds.), Proceedings of the 37th Annual Conference of the Cognitive Science Society (pp. 2721-2726). Austin, TX: Cognitive Science Society.

Yamauchi, T., Seo, J. H., Jett, N., Parks, G. & Bowman, C. (2015). Gender differences in mouse and cursor movements. International Journal of Human Computer Interaction 31, 911-921.

Yamauchi, T., Xiao, K., Bowman, C., Mueen, A. (2015). Dynamic time warping: A single dry electrode EEG study in a self-paced learning task. *2015 International Conference on Affective Computing and Intelligent Interaction* (ACII). pp. 56-62. IEEE Computer Society.