Spatial attention control mechanism modulated by subliminal stimuli:

An Electroencephalography Study

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List of Abbreviations

EEG	Electroencephalography
ERP	Event Related Potentials
EDAN	Early Directing Attention Negativity
ADAN	Anterior Directing Attention Negativity
LDAP	Late Directing Attention Positivity
SOA	Stimulus Onset Asynchrony
AST	Attention Schema Theory
TPJ	Temporal Parietal Junction
ROIs	Region of Interests
MUA	Mass Univariate Analysis

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Abstract

The relationship between attention and consciousness has been a long-lasting debate. Considerable evidence suggests that it is possible to attend to a stimulus without being aware of it. Here we investigated the role of awareness in the spatial attention control mechanism. Specifically, the current study used the event-related potential (ERP) technique to investigate the effect of a subliminal distracting prime on the temporal dynamics of the spatial attention control system.

Metacontrast masking rendered the subjects either objectively aware or unaware of a task-irrelevant prime that provided consistent or conflicting information to the task. The task was a Posner cueing paradigm that facilitated subjects' endogenous orienting of attention to a location, signaled via a symbolic cue. The control mechanism of spatial attention was examined via three ERPs, EDAN, ADAN, LDAP, observed during the time interval after the cue onset.

Results revealed that a task-irrelevant invisible prime that provided conflicting information to the task-relevant cue created greater disturbance to the endogenous orienting of attention, compared to an incongruent but visible prime, reflected upon a reversal polarity in the ADAN. Further, the disruptive effect of the prime was transient, as the LDAP component was left unaffected by the distracting prime.

These findings add to the growing information on the temporal dynamics of attention control mechanisms, and confirmed one of the hypotheses proposed by Attention Schema Theory of consciousness. Together, the current finding suggested the existence of an endogenous attention control system that is unable to establish speedy inhibition to an invisible distractor.

Chapter 1: Introduction

1.1 Spatial Covert Attention

We are constantly bombarded by an overwhelming amount of visual information in everyday life, though only a fraction of stimuli that hit the retina eventually reach a cognitive stage of processing. Because of the limited capacity of our cognitive systems for processing incoming signals in the brain, the ability to filter out irrelevant information becomes crucial. Attention is often defined as the selection processes of the brain which result in signal enhancement and subsequent further processing of a subset of the available sensory information, and which ultimately have behavioral consequences (Graziano, 2020).

Few would dispute that the relationship between visual attention and the oculomotor system is an intimate one. While much of our abundant visual experience is the result of fast eye saccades that actively shift attention around the surrounding environment, selective attention can also be shifted “covertly”, independent of eye movements (Posner, 1980). That is, attention can be allocated to the periphery within the visual field, without directing one’s gaze towards the location. Covert attention provides evolutionary and social benefits as it allows us to monitor the environment and to guide subsequent goal-directed eye gaze. Overt and covert attention together constitute spatial attention, an umbrella term that refers to attention directed to a relevant location in space, similar to how a “spotlight” (Posner, 1980) moves and in turn enhances signal processing within a circumscribed region of space.

One way to categorize spatial attention is by whether its focus is externally and involuntarily driven or is internally, voluntarily controlled, namely, exogenous and endogenous attention, respectively. Exogenous attention, or bottom-up selection processes, involve involuntary orienting to salient stimuli (Jigo et al., 2021) in the environment. A salient object is able to capture exogenous attention automatically because its critical feature stands out from the rest of the scene, such as a black horse in a herd of white sheep (Mulckhuyse & Theeuwes, 2010). This process is proposed to be modulated by sensory stimulation originating from the dorsal posterior parietal and frontal cortex (Wilterson et al., 2021). Endogenous attentional selection occurs when an agent volitionally directs attention to a stimulus in the environment, even if it is not the most salient one. More specifically, it is the prioritization of stimulus processing related to intention or tasks and is controlled predominantly by the right hemisphere, centering on the temporoparietal and ventral frontal cortex (Wilterson et al., 2021). For example, in a visual task where the goal is to find a black horse among other black animals and different colored horses, the black horse will be selected by endogenous attention because it is what we are looking for.

Both attentional control mechanisms, though operating at functionally distinctive levels, are critical to the formation of visual representations of stimuli and for the guidance of behavior (Hickey et al., 2010).

1.1.1 Why EEG to Study Spatial Attention?

Neurons generate two electrical signals, *action potentials* and *postsynaptic potentials*. When a neuron fires, the action potential propagates from the beginning of an axon to the terminal, where the neurotransmitters are released. When the neurotransmitters bind to receptors on the membrane of the postsynaptic cell, a postsynaptic potential is generated, facilitating the opening and closing of ion channels. Because of how the action potentials are generated and summated, scalp electrodes can mostly capture postsynaptic potentials but not action potentials (Luck, 2012). Electroencephalography (EEG) is a track of the summation of postsynaptic activity recorded from electrodes attached to the human scalp. In a typical EEG experiment, raw EEG activity will be recorded concurrently from multiple electrodes when stimuli are presented to subjects. Conceptually, the stimulus-elicited EEG activity should contain brain activity reflective of the stimulus processing plus external and internal noise unrelated to the information processing. If we average the segments of EEG waveforms across many trials, we can preserve the consistent stimulus-elicited brain activity while eliminating the noise, which is random in its relation to the timing of the stimulus presentation. The resulting EEG segments, termed Event related potentials (ERPs), consist of several positive and negative voltage deflections, termed *peaks*, *waves*, or *components* (Luck, 2012). The order of ERP peaks reflects the temporal sequence of different stages of information processing in the brain.

Because of its temporal precision and sensitivity, ERPs have been used extensively in cognitive neuroscience research, including studying the interaction between endogenous and exogenous attention. Endogenous attention, as mentioned earlier, is relevant to an agent's current task and thus requires more cognitive effort. It is thereby a few hundred milliseconds slower to deploy compared to exogenous, reflexive attention shifts that are automatic but transient, occurring within 100ms after a visual stimulus onset. The temporal proximity between exogenous and endogenous attention makes EEG an ideal tool to study sub-stages of attentional control.

1.1.2 Posner Cueing Paradigm: A Classical Design to Study Spatial Attention

In the lab, a main way to study endogenous attention is by using symbolic cues predictive of the location of a target stimulus. Exogenous attention is typically modulated using a salient stimulus presented at the periphery that is irrelevant to the ongoing task. Posner cueing paradigm is a widely used design that combines the two manipulations. A centrally presented cue, such as an arrow or a location word (or any arbitrary symbol), is usually associated with symbolic meaning that instructs the subjects to shift attention to a particular location on the screen. The implicit or explicit learning of the spatial meaning of the cue is important in facilitating an endogenous orienting of attention to the cued location (Lambert et al., 2006). By contrast, exogenous cues do not need to predict the target location. Instead, it is the saliency property of the cue that directs reflexive spatial attention to its location.

Posner cueing paradigm allows us to isolate the brain activity related to different time-courses of endogenous and exogenous attention, without the perturbations of other concurrent sensory or cognitive processes. A minimal amount of stimuli are included in a typical Posner cueing design: a central fixation cross, a central symbolic cue, a target, and a distractor that captures exogenous attention. Each of the stimuli is presented in sequence and is relatively partitioned temporally, leaving a period of time after its onset to allow for sensory processing. As a result, we can select any time window to investigate the processing related to any stimulus: post-cue interval to explore the preparatory orienting of attention, post-target interval to explore the enhanced processing of a location over another as the result of selective spatial attention, post-distractor interval to examine any neural signals in response to the task-irrelevant information.

1.1.3 Electrophysiological Evidence for Spatial Attention Modulations

Traditional experiments investigating attentional modulation on the target are often time-locked to the target onset for ERP analysis. However, the brain activity recorded after target onset may reflect an attention implementation mechanism, such as amplification of the selected sensory information, or response output, or updating cue-target relationships, instead of an actual attentional control mechanism *per se*.

When a valid cue appears that is predictive of the subsequent target location, even before the target onset, the attention control mechanism will already be functioning, preparing to enhance target processing at the cued location. Thus, an alternative approach of looking at EEG data is to examine ERPs when time-locked to the cue onset. Again, the classical Posner cueing paradigm allows us to look at the post-cue brain activity because there is a time interval between the cue and the target onset.

Covert attention shifts triggered by spatial cues are associated with three lateralized ERP components: early directing attention negativity (EDAN) around 150-

400ms, anterior directing attention negativity (ADAN) around 300-500ms, and late directing attention positivity (LDAP) around 500ms-700ms after cue onset (Meyberg et al., 2017). EDAN is related to the processing of directional information from the cue, and is elicited when subjects attend to a lateralized part of the cue itself (McDonald & Green, 2008). For example, a common shape of the spatial cue is an arrow; the EDAN elicited in response to the arrow cue might entail subjects attending to the arrowhead in order to process the spatial location. ADAN is generally regarded as the initiation of spatial attention reallocation. LDAP, occurring later in time, has been interpreted as marking a selective preparatory biasing of neural activity in visual areas, that subsequently results in selective processing of targets at attended locations (Jongen et al., 2007). Thus, the ADAN and LDAP are commonly implicated as neural markers of executive processes of endogenous control. The above electrophysiological studies have together established a temporal sequence of spatial attention control under the Posner cueing paradigm: symbolic cues take around 150ms to be interpreted (EDAN), in order to facilitate endogenous attentional shifts (ADAN) to enhance processing at the target location (LDAP), whereas the distracting cue presented at periphery attracts an automatic, bottom-up attention within 100ms post cue-onset (Carrasco, 2011).

1.2 Consciousness and Unconsciousness

Decades of consciousness research have not yet yielded a crisp, acceptable definition. Here I take the contextual definition of consciousness from E. Roy John:

> Consciousness is a process in which information about multiple individual modalities of sensation and perception is combined into a unified multidimensional representation of the state of the system and its environment, and integrated with information about memories and the needs of the organism, generating emotional reactions and programs of behavior to adjust the organisms to its environment (Thatcher & John, 2021).

What stands out in the above definition is its inclusivity as it opens up possibilities for different subcategories and sub-mechanisms underlying the umbrella term of consciousness. In the current study, I focus on the contents of conscious perception rather than the states of consciousness. Conceptually, consciousness has two forms: *phenomenal consciousness* is the subjective state of awareness, or the very personal feeling of being aware; *access consciousness* is the content accessible to higher cognitive processes including memory, language, decision-making, and control of voluntary behavior. In the same vein, Graziano and colleagues proposed two alternative categories of consciousness that share many similarities to the access and phenomenal categories of consciousness: *I-consciousness* (I for information) refers to the information in the brain that can be selectively enhanced and processed by higher cognitive processes, whereas *m-consciousness* (M for mysterious) is the more mysterious subjective experience that people claim to accompany the context-based awareness (Graziano, 2020), which can be mapped on to *phenomenal consciousness.*

A commonly accepted strategy to isolate neural correlates of consciousness has been to analyze the contrast between brain activity when subjects are conscious versus not conscious of a stimulus, while the physical differences between these two conditions are kept minimal. Visual masking paradigms are a common way to minimize the physical differences while establishing conscious and non-conscious conditions.

1.2.1 Visual Masking Paradigm

Our steady and continuous visual experience relies on highly dynamic underlying neural processes that updates and reconstructs several times per second (Breitmeyer & Ogmen, 2006). According to this view, the visual system operates in a transient regime, such that the neural response to one stimulus can interact and even affect the processing of another stimulus, if they are presented sequentially and close in time. Therefore, visual masking paradigms provide a powerful tool to investigate the time course and stages of visual processing that lead to conscious or unconscious perception.

Visual masking paradigms have been used extensively to study visual processing. Visual masking refers to a procedure during which the visibility of a stimulus, termed target, is attenuated by a spatiotemporally adjacent or overlapping stimulus, termed mask (Breitmeyer, 1984; Woodman & Luck, 2003). The strength of the masking depends on the choice of the stimulus, mask, timing, and task parameters. Stimulus and display related parameters include luminance, contrast, shape, size, etc.; timing parameters include the duration of the target and the mask, and the time interval between the target and the mask. The time interval, commonly referred to as Stimulus Onset Asynchrony (SOA), is an especially crucial determinant for the visibility of the target. When the mask precedes the target at negative SOAs, the design is called forward masking; when the mask follows the target at positive SOAs, the design is termed backward masking.

Metacontrast masking is a type of backward masking that has been used widely to explore the field of subliminal perception. It includes a target followed by a mask whose contour fits neatly around the target stimulus (Koster et al., 2020). Metacontrast masking yields a U-shaped function, called Type-B function, as a function of SOA and its masking effect. That is, the masking strength is negligible when target and mask onsets are simultaneous or when the SOA >150ms; the masking effect is most optimal at intermediate SOA, around 40-100ms.

Common methods to assess the awareness of a target stimulus in the metacontrast masking paradigms include a variety of objective and subjective measures. Objective measures refers to the correct discrimination of the identiy or a specific feature of a target stimulus (diamond vs square, apple vs banana). In contrast, subjective measure accounts subjects' reports of their perception of the stimulus. It restricts the reports to predefined categories, such as correct vs incorrect, seens vs unseen. Measuring implicit perception in such a way assumes the subjects to have optimal access to their conscious content, which is not always accurate- for example, a patient with blindsight that is cortically blind due to lesions in their primary visual cortex, can still respond behaviorally to visual stimuli that they cannot consciously see. In addition, in studies where awareness is subjectively reported on a sliding scale, the problem becomes that subjects often treat "uncertainty" as a lack of perception, leading to another inaccurate reflection of their awareness state (Hannula et al., 2005).

Another limitation of subjective awareness related to metacontrast masking is that it doesn’t provide a pre-established criterion content. Criterion content is the standard by which subjects’ awareness decision is judged. Metacontrast masking effect strongly depends on the specific criterion measure that is used (Breitmeyer & Ogmen, 2006). In subjective measures, the criterion content is chosen by the subject; whereas objective measures, such as shape discrimination, restricts the criterion content to specific stimulus attributes (Koster et al., 2020). Thus, many metacontrast studies investigating unconscious processing adopt an assessment of conscious access to stimulus features (Mattler, 2003; Palmer and Mattler, 2013).

1.3 The Relationship Between Attention and Consciousness

A fundamental question in consciousness research concerns the relationship between attention and awareness. When we distribute our attention to an item, we often become aware of its attributes, at the cost of becoming less conscious of the unattended items (Cohen et al., 2012). Following this intuitive assumption on the inextricable relation between attention and consciousness, some scientists hold a single-dissociation view, favoring the argument that attention is necessary yet insufficient to give rise to consciousness; under this claim, attention can be directed to stimuli without the awareness of it, but not vice versa, i.e., it is impossible to be aware of a stimulus that is completely unattended (Cohen et al., 2012; Mack & Rock, 1998). On the contrary, emerging theories have claimed a double-dissociation between the two, proposing two independent, distinct neural mechanisms that give rise to attention and consciousness (Koch & Tsuchiya, 2007); supporting evidence mainly comes from experiments where perceptual awareness is reported when attention is minimal. To date, numerous studies have confirmed the existence of some forms of attention even when the stimuli are subliminal, indicating the possibility of attention without awareness; attempts have been made to isolate consciousness from any attentional mechanism, though, the conclusions remain controversial and many suffer from experimental design flaws (Maier & Tsuchiya, 2021; Pitts, Lutsyshnia, & Hillyard, 2018).

1.3.1 The effect of unconscious stimuli on visual-spatial attention

Classic theories of attention control proposed that unconscious processing is automatic, involuntary, without the interference of higher-order cognitive control, such as top-down attention and task goals. This view has been recently challenged by newly emerged theories and experimental evidence proclaiming that unconscious processing critically relies on top-down control factors (Prasad & Mishra, 2019). One of the first empirical evidence that tested the effect of subthreshold stimuli on cognitive control came from Tsushima and colleagues (2006): they found that task-irrelevant visual stimuli, when not consciously perceived by the subjects, led to a stronger disturbance in the task performance compared to visible task-irrelevant stimuli. The researchers concluded that the brain cannot facilitate effective inhibitory control over subthreshold distractors and are thus more prone to be affected by it. This striking finding has become one of the main foundational pieces for a series of emerging perceptual learning models and attention control theories (Graziano et al., 2020; Roelfsema et al., 2010). Here we introduce one of the related theories, Attention Schema Theory, that proposes a novel way to explain the neural basis of subjective awareness.

1.4 Attentional Schema Theory: a new view on the relationship between attention and consciousness

Major theories of consciousness have proposed different arguments for the association or dissociation of attention and consciousness. A newly emerged theory of consciousness, Attention Schema Theory (AST), introduces an approach to tackling the problem, accompanied with some preliminary yet promising behavioral and neuroimaging evidence (Bio & Graziano, 2021; Blackmore, 2020; Camacho & Bordons, 2007; Devaney et al., 2019; Graziano, 2020; Graziano et al., 2020; Steel, 2021; Webb et al., 2016; Wilterson et al., 2020, 2021). According to the theory, when visual attention is directed to a stimulus, such as an image of an apple, the selective processing of the image results in an accurate depiction of stimulus attributes, such as the color, the shape, the location in space, etc. However, the selective processing of the apple alone does not give rise to the conscious report of the apple ("I am aware of the red apple"); it only provides a visual representation of the apple ("the red apple"). In order for the brain to conclude a subjective report of the apple, more information is needed: it requires the brain to contain information about the self ("I") and a link that connects the self and the physical apple image together ("am aware of"). AST proposes that the process that gives rise to a stable visual representation of an apple ("the red apple") is attention (Graziano & Webb, 2015). The visual representation is the result of selective processing and enhancing of a subset of information signals in the brain, leading to information broadcasting between cortical regions involved in cognitive and motor functions (Graziano et al., 2019). An internal model of the self is built from information about the physical structure of the body, and results in a "first-person perspective".

The link that binds the self model and the perceptual model together and makes the conscious report possible contains information about *how* the brain attends, selectively processes and facilitates bodily action (Graziano & Kastner, 2011). The link is essentially a model that represents fundamental properties and functions of attention, termed attention schema. What's more, it is the attention schema that gives subjective awareness its "ghostly" feeling. Consider the above statement "I am aware of the red apple". This seemingly concrete statement has two layers of consciousness: a set of information accessible to our conscious report (i-consciousness/access consciousness) and the personal, experiential property of being in a state of awareness (m-consciousness/phenomenal consciousness). While the actual attention gives rise to the former part, the latter introspective, “ghostly” experience is the result of the attention schema.

The attention schema is a control model of attention that the brain constructs that allows for more efficient processing and organizing of information. Attention, after all, can facilitate behavior. You are more likely to react to an attended item than to an unattended one. Thus, it is important to have a model of attention that provides prediction of behavior based on past history. This internal model of attention is also important to govern attention itself. Attention is a highly dynamic and complex system. In order to control a sophisticated system, such as attention, it is helpful to build a simplified model of the system (Camacho and Bordons Alba, 2004; Graziano & Kastner, 2011). In the control of attention, the simplified model of the actual attention, namely the attention schema, continuously updates a set of online information for monitoring and processing, and makes predictions about where and what we will be attending to momentarily (Graziano et al., 2019). It should be noted that top-down (endogenous) control of attention, but not bottom-up (exogenous) attention, requires such a control model. This is because exogenous attention is reflexive and automatically attracted to a location in the visual space.

Importantly, this internal model, or the attention schema, is a simplified and thus sometimes inaccurate model of the actual selective attention configuration. The attention schema doesn’t need to contain every mechanistic and cellular detail of the selective processing that’s happening in different neural networks at microscopic and macroscopic level; or it won’t be as efficient.

Following the arguments of AST, a testable hypothesis of the theory is as follows: in the condition of attention without awareness, some forms of attention may remain functional (i.e. exogenous attention that doesn't require an internal model). Nevertheless, the endogenous control of the attention should be impaired (because without a model of attention, i.e. "awareness", it's much more difficult to control attention). The function of endogenous attention control is essentially enhancing the processing of a desired location, feature, or object in the visual field while inhibiting processing of task-irrelevant signals. Thus, an impaired endogenous attention control can result in uninhibited distractor information that takes more cognitive resources, subsequently leaving fewer resources for the task-relevant information (Tsushima et al., 2006). The finding by Tsushima and colleagues (2006) mentioned above, according to this hypothesis, can be interpreted as an impaired attention control model and a subsequent failure of distractor inhibition.

To test this hypothesis using behavioral paradigms, Wilterson and colleagues (2020) designed a series of experiments employing a spatial cueing design while manipulating the visibility of cue, in order to control the endogenous and exogenous attention shifting induced by the visible or invisible cue. The results indicated that the cue-target relationship could be established implicitly. In contrast, when the subjects were not aware of the cue, the exogenous attention effect remained, but the endogenous attention effect was missing, consistent with the predictions of AST. Subsequent fMRI findings found that right temporal parietal junction (TPJ) activation is associated with the endogenous effect and may be part of the neural circuitry that creates the online attentional model. Both the behavioral and the neuroimaging results have laid a substantial step toward understanding different attentional mechanisms operating in the brain and how awareness interrelates with attention. Nevertheless, due to the poor temporal resolution of the fMRI and the inability to examine any innate brain processes from behavioral evidence, the extent to which a subliminal visual stimulus affects the temporal sequence of the attention control mechanism is left unanswered.

As stated earlier, the LDAP component is regarded as a reliable neural marker of top-down attentional modulation, distinguishing itself from other ERP components which can be driven by both external sensory stimulation and endogenous attention, such as the EDAN component. ADAN is also a possible neural signature modulated by the initiation of endogenous attention. Relating back to Attention Schema Theory, it seems reasonable to propose that ADAN and LDAP can reflect the activation of the so-called “attention schema”, or perhaps be markers of the attentional mechanism that is subsequently modeled by the schema: when subjects are aware of a prime followed by a cue, the endogenous attentional mechanism should be active, resulting in a typical spatial-temporal topography of ADAN and LDAP; in contrast, when subjects are not aware of the prime, such prime-cue relationship is absent, resulting in an impaired control model of selective attention. In this case, ADAN and LDAP might result in temporal delay, spatial displacement, or complete absence.

1.5 Toward a Design to Study Attention Control of Subliminal Visual Stimuli

To provide a brief summary of the methodology in the study of attention and consciousness mentioned above, metacontrast masking has been widely regarded as a powerful tool to study subliminal conscious perception, while Posner cueing paradigm is commonly used to study time-courses of endogenous and exogenous attention. Therefore, a possible experimental paradigm to study the relationship between attention and unconscious perception would be to combine a metacontrast masking with a Posner cueing design.

Mattler (2003) developed a metacontrast masking priming-cue design to study the effect of masked stimuli on motor and nonmotor systems. On each trial, the participants had either a pitch recognition or timbre identification task to perform. The trial began with a briefly presented prime, followed by a mask/cue at the same location. The location of the mask/cue indicated the task in effect. Prime was masked thus not consciously accessible to the subjects, though it was predictive of the subsequent cue location. Palmer and Mattler (2013) further refined the paradigm to explore the effect of masked prime on endogenous shifting of spatial attention. The prime and cue were both presented at the center and had the same contour shape. The prime was masked and the subjects were not informed of the existence of the prime. The contour shape of the cue instructed the subjects to shift their attention to either left or right side of the screen, where they had to perform a target discrimination task. In a nutshell, the refined priming-cue paradigm was a metacontrast masking paradigm followed by a Posner cueing design. The SOA between the prime and the cue could be modified to control the visibility of the prime; the shape of the prime and the cue can be either congruent (same shape) or incongruent (different shapes), thereby making the prime as a distracting information to the task in half of the trials. The researchers mainly used the paradigm to examine the behavioral consequences of subliminal priming, such as reaction time and task performance. Nevertheless, the design is also an ideal setup to examine the electrophysiological signatures of subliminal priming, due to the sequential presentation of the prime, the cue, and the target. More importantly, the cue and the target together constitutes a typical endogenous attention shifting task. Typical neural signatures of endogenous control of attention should be present (ADAN and LDAP) between the cue and the target onset, once a symbol association learning between the shape of the cue and the location it entails has been established. The addition of the prime, a piece of information that is consistent or inconsistent with the ongoing task and is invisible or visible to the subjects, would allow us to explore its effect on an already established attention control system.

1.6 The Current Study

The goal of the current study was to use the ERP technique to explore the spatial attention control mechanism modulated by subliminally presented visual stimuli. The overall design was built on the metacontrast priming cue paradigm developed by Palmer and Mattler (2013) with refinements optimized for EEG data collection. On every trial, a task-irrelevant prime that was rendered invisible in half of the trials preceded a symbolic cue that instructed the subjects to shift to the left or right side of the screen in order to complete the task. The cue also served as a metacontrast mask to the prime. The prime and the cue were both symbolically indicative of the location of the subsequent target, yet there were incongruent and congruent trials in which the prime and the cue had different or the same shapes. Subjects, instructed to only pay attention to the cue-target association, performed a discrimination task on the cued location. Together the approach constituted a 2 (awareness) x 2 (congruency) x 2 (cue locations: left/right) within-subject design. A pre-test was carried out to adjust the prime-cue SOA to individuals' invisibility threshold.

The time interval after the cue onset was the main time window of interest. Three ERP components, EDAN, ADAN, and LDAP were the focus of analysis. I hypothesized that, in general, when the invisible prime was incongruent to the cue and offered conflicting information to the ongoing attention task, it would create a larger perturbation on the endogenous attention control. Some neural signatures of an impaired attention control could possibly include: a greater within-subject variance of the ERP amplitude, a delay of the ERP peak, a decrease or increase of the ERP amplitude, an absence of the ERP component, or a different topography distribution of the ERP.

Overall, the current study could add empirical evidence to test existing theories of attention control and consciousness. It also has practical implications: a functional and intact attention control mechanism is essential for everyone to accomplish the goals that we want to achieve. But distractors are everywhere, interfering with our sustained attention on the task. This study could provide some understanding of our enemy, the distractor, and hopefully for the ultimate goal of conquering it.

Chapter 2: Method

2.1 Overview

The proposed 2x2 design, after collapsing across left-right cues/targets, yielded 4 experimental conditions for comparison in the behavioral and brain data analyses: 1) prime-aware, prime-cue congruent; 2) prime-aware, prime-cue incongruent; 3) prime-unaware, prime-cue congruent; 4) prime-unaware, prime-cue incongruent.

The main analysis of interest was the interaction between congruency (of the prime-cue) and awareness (of the prime). The prime-cue congruency manipulation was intended to influence the extent of attentional control: in the congruent trials, the symbolic information conveyed by the prime and cue were consistent and accurately reflective of the spatial location that the subjects had to attend to, thus serving as a baseline for an intact, undisturbed attentional control system. Conversely, in incongruent trials, the symbolic information delivered by the prime and the cue were contradictory, thus potentially disrupting the attention control system, with the prediction that awareness may modulate the extent of this disruption (hence the focus on the interaction effect between congruency and awareness). Though subjects were informed that the cue was always valid, their spatial attention would nevertheless be affected by the task-irrelevant prime, either endogenously (aware of the symbolic information it conveys as it relates to the target discrimination task) or exogenously (not aware of the symbolic information conveyed by the prime, yet bottom-up attention may still be influenced by the prime in the unaware condition). Given that endogenous attention was modulated by an internal control system, as proposed by AST, under aware conditions, attention should be less affected by the inaccurate (incongruent with the cue) prime. If the congruency effect was larger in the unaware condition than in the aware condition, we would interpret such finding as consistent with AST: when subjects were unaware of the prime, the attention control model was impaired and was thus unable to accurately regulate attentional allocation to the location indicated by the cue; when subjects were aware of the prime, they were more able to actively suppress the influence of the incongruent prime, yielding a smaller congruency effect.

2.2 Stimuli

Both the prime and the cue resembled the stimuli used by Palmer and Mattler (2013), which were simple black geometric diamond and square shapes (Fig. 1B). The primes were small solid diamonds or squares, while the cues were larger outline diamonds or squares with the inner contour containing both diamond and square outlines, such that if presented simultaneously, the primes would fit snugly inside the cues. This design allowed the cues to also serve as metacontrast mask to the preceding primes; the visibility of the prime can be modulated by manipulating the time interval between the prime and cue onset, typically referred to in the literature as the “stimulus onset asynchrony” (SOA). Subsequent to the cue, two gabor patches slightly tilting left or right by 15° appeared on each side of the screen (Fig. 1C), at the center of a four-dot location marker. The square shaped cue instructed subjects to attend to the left gabor patch to make an orientation judgment, and the diamond shaped cue instructed subjects to attend to the right gabor patch to make an orientation judgment.

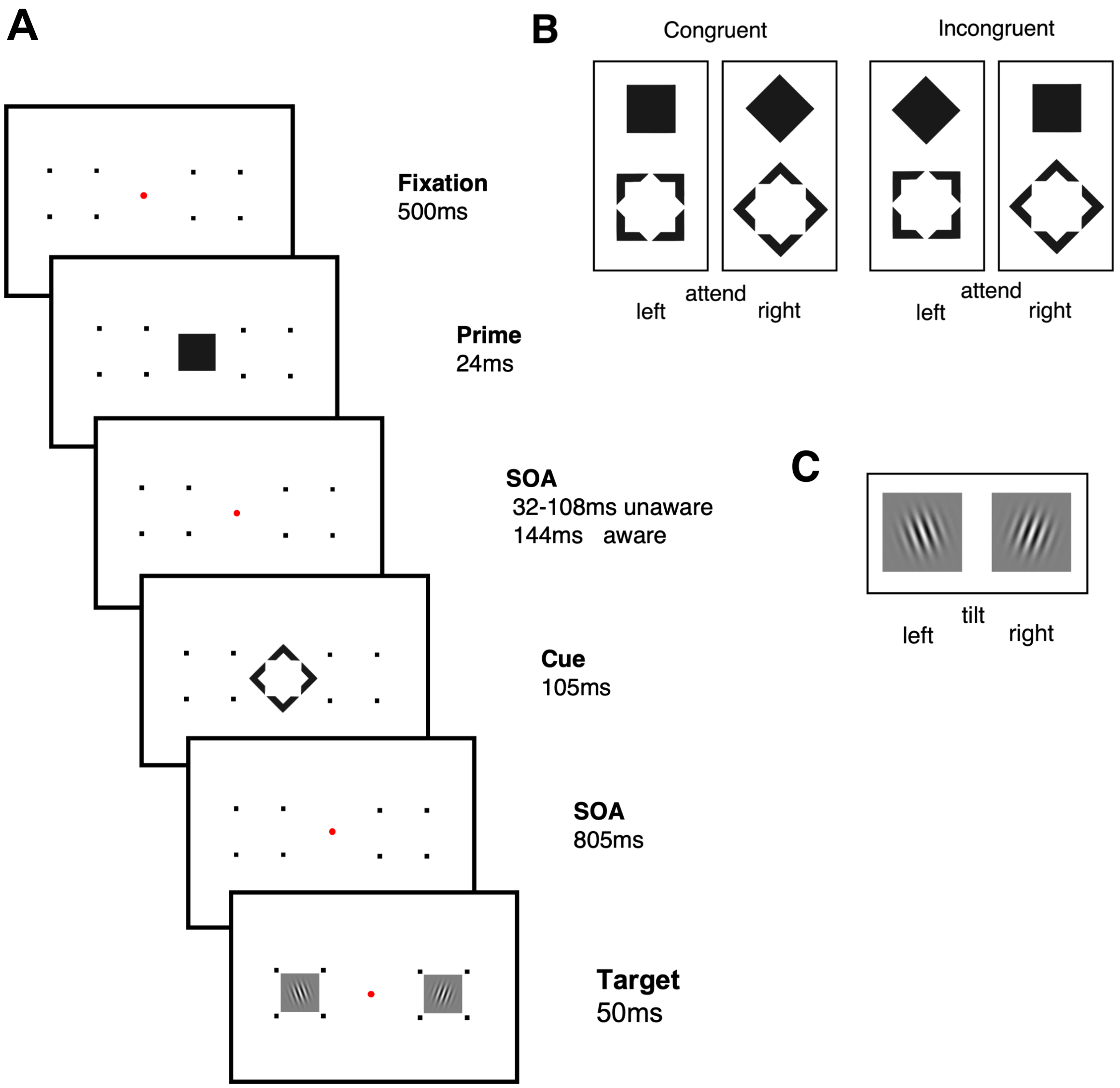

Figure 1: Stimuli and procedure in the experiment. (A) Sequence of events in a trial. (B) Possible combinations of prime and cue stimuli. (C) The Target stimuli, consisting of two tilted Gabor patches.

2.3 Procedure

Participants were invited to two experimental sessions, with the first lasting 10 min and the second 1 h. Participants were instructed to sit comfortably in front of a computer screen (refresh rate of 120Hz) in a dimly lit, sound-attenuated, electrically shielded room. Stimuli were presented on a 27 inch monitor at a viewing distance of 70cm. The recording of reaction time (RTs) was performed with Presentation software (Neurobehavioral Systems), and the recording of EEG data was performed in the BrainVision Recorder (Brain Products). The first session was a pre-test to determine SOA values for lowest visibility. The second session began with a training block (40 trials), and then 10 experimental blocks (100 trials per block) of the spatial cueing tasks. The 2(visibility) x 2(prime-cue congruency) x 2(left vs right attending location) design yielded 125 trials for each condition. Each condition was presented randomly within a block, and there were a total of 12-15 trials per condition falling within each block.

2.3.1 QUEST Pre-task procedure

Presentation of stimuli was programmed in Matlab (Psychtoolbox). Following a brief explanation of the task and a training block, the visibility threshold of the prime followed by the metacontrast mask was measured using QUEST algorithm, as described below.

The QUEST algorithm is an adaptive staircase procedure used to quickly estimate one's perceptual threshold based on a psychometric function from a sequence of trials (Watson & Pelli. 1979, 1983). A psychometric function entails the relationship between a physical feature of a stimulus and the probability of a particular psychophysical response (Watson &Pelli, 1983). In the current study, the physical feature of a stimulus was the visibility of the prime, as modulated by the prime-cue SOA, while the response was "yes(recognizable of the shape)" or "no(unrecognizable)". Because the shape was the response criterion content that determined the choice of response, the task was defined as an objective measure of the awareness. As mentioned in Chapter 1, the function of a metacontrast masking paradigm of the visibility against SOA yields a U-shaped curve, with intermediate SOA yielding the lowest visibility of the cue (i.e. the most "no" responses) at intermediate SOAs and higher visibility of the cue (i.e. more "yes" responses) at lower and higher SOAs. The final output of QUEST, the threshold value, was an exact number of the prime-cue SOA that resulted in a 50-50 distribution of the "yes" or "no" answer. QUEST, based on the assumption that a psychometric function is invariant in form when expressed as a function of log intensity, takes use of the psychophysical response and delivers a maximum likelihood estimate of the response threshold on a trial-by-trial basis. In other words, an estimate of the threshold is calculated by the algorithm after inputting the response after every trial, and subsequently, the physical feature of the stimulus (in this case, the SOA between the prime and the cue onset) is adjusted for the next trial. The final estimate of the SOA was calculated after 80 trials, and the value was used as the prime-cue SOA for the "unaware" condition in the subsequent priming cue task for that individual subject. Subjects generally displayed a variety of SOA values, with an average of 45.1ms (SD = 25.6; Max = 84.1; Min = 8.0).

After a brief introduction to the stimulus sequence and a short practice round, a short training period of 40 trials followed, with a central fixation cross for 250 ms, followed by a central prime for 24 ms, and a central cue for 105 ms. After the cue disappeared from the screen, the subjects were instructed to press either "LEFT" or "DOWN" key to indicate whether they could clearly recognize the prime being a square or a diamond, or if they were unsure, respectively. A final SOA value was displayed on the screen, if it fell between 20-85ms, the subject could continue to the real QUEST task, which was the same as the training but longer (80 trials). Otherwise, the subject was asked to repeat the training once again and then proceeded to the real session. This was to ensure that subjects were really reporting the recognizability of the shape, instead of the visibility of the prime (i.e. identification vs. detection of the prime shape).

2.3.2 Priming cue Task

Presentation of stimuli was programmed in Neurobehavioral Presentation software (Fig. 1A). Prior to the experiment, the participants were told that this task was irrelevant to the previous one, so that the subjects would focus on their cueing task while not paying excessive attention to the prime. Each trial started with the presentation of a central fixation dot (size 1°x 1°) and two location markers consisting of four dots around an imaginary square. After 500ms a prime was followed by a cue after some prime-cue SOA. For the unaware condition, the prim-cue SOA was determined by the QUEST pre-task output. For the aware condition, the prime-cue SOA was 144ms. The number was based on the original study by Palmer and Mattler (2013). I chose a fixed SOA for the aware condition because it is easy to find a value that consistently leads to the stimuli always being seen by all subjects, whereas the lowest point in the U-shaped function of metacontrast masking strength (i.e the point that gives the lowest visibility of the stimuli) vary across subjects.

Within each trial, a fixation dot appeared at the center of the screen for 500ms, immediately followed by a centrally presented prime for 24ms. After a short period of SOA, a cue appeared for 105ms. The prime and cue were both symbolically informative of one of the spatial locations the subjects were asked to attend to in the target task. A diamond shape indicated attending to the right, and a square shape indicated attending to the left (Fig. 1B) After 805ms of SOA, two gabor patches slightly tilting left or right by 15° appeared on the left and the right side of the fixation dot, at the center of a four-dot location marker. Subjects were asked to button-press to indicate if the Gabor patch at the attended location (as instructed by the cue) was tilting to the left or to the right (Fig. 1C). The subjects used two assigned buttons on the response box to respond to the tiltness of the Gabor patch on a trial-by-trial basis, and all responses were made after the target onset.

2.4 EEG Recording and ERP pre-processing

Electroencephalography (EEG) was recorded non-invasively from the scalp using a 64 channel EasyCap system (Brain Products, Garching, Germany). Electrode impedance was kept below 10kΩ. Electrode signals were sampled at 500Hz and amplified by BrainVision "Professional BrainAmp" amplifiers. Raw data was filtered online with a high cutoff at 150 Hz and offline with a high cutoff at 25 Hz. A right mastoid electrode ("Ref") served as the reference while recording for all channels, and data were re-referenced offline to the average of the two mastoids. Two electrodes were placed at the temples on each side adjacent to the left and right eye (HEOG: 62, 63) to detect horizontal eye movement artifacts. One electrode was placed directly below the left pupil (VEOG: 61) to detect vertical eye blink artifacts. See Fig. 2 for a complete electrode assignment on the scalp.

During ocular artifact rejection processing, trials with large eye movements (150-250uV for eye blinks, 70-90uV for eye movements) were rejected prior to averaging. Trials were discarded if they contained eye blinks, eye movements, or other muscle artifacts in a -400ms to 800ms time window. On average, 11.3% of trials were rejected due to these artifacts, and 3 subjects with >20% trials rejected were excluded from analysis due to an insufficient number of trials to obtain reliable brain activity. Individual electrodes demonstrating extended periods of noise were replaced by interpolated signals from adjacent electrodes. Most of the interpolated electrodes were at the outermost ring of the cap, such as at the back of the neck or at the hairline. The ERP data was segmented from -400ms to 800ms relative to the cue onset. ERPs were time-locked to the onset of the cue, and baseline corrected from -400ms to -200ms. This baseline was chosen for correction because the prime occurred between -200ms to 0ms and was expected to elicit ERPs prior to the onset of the cue.

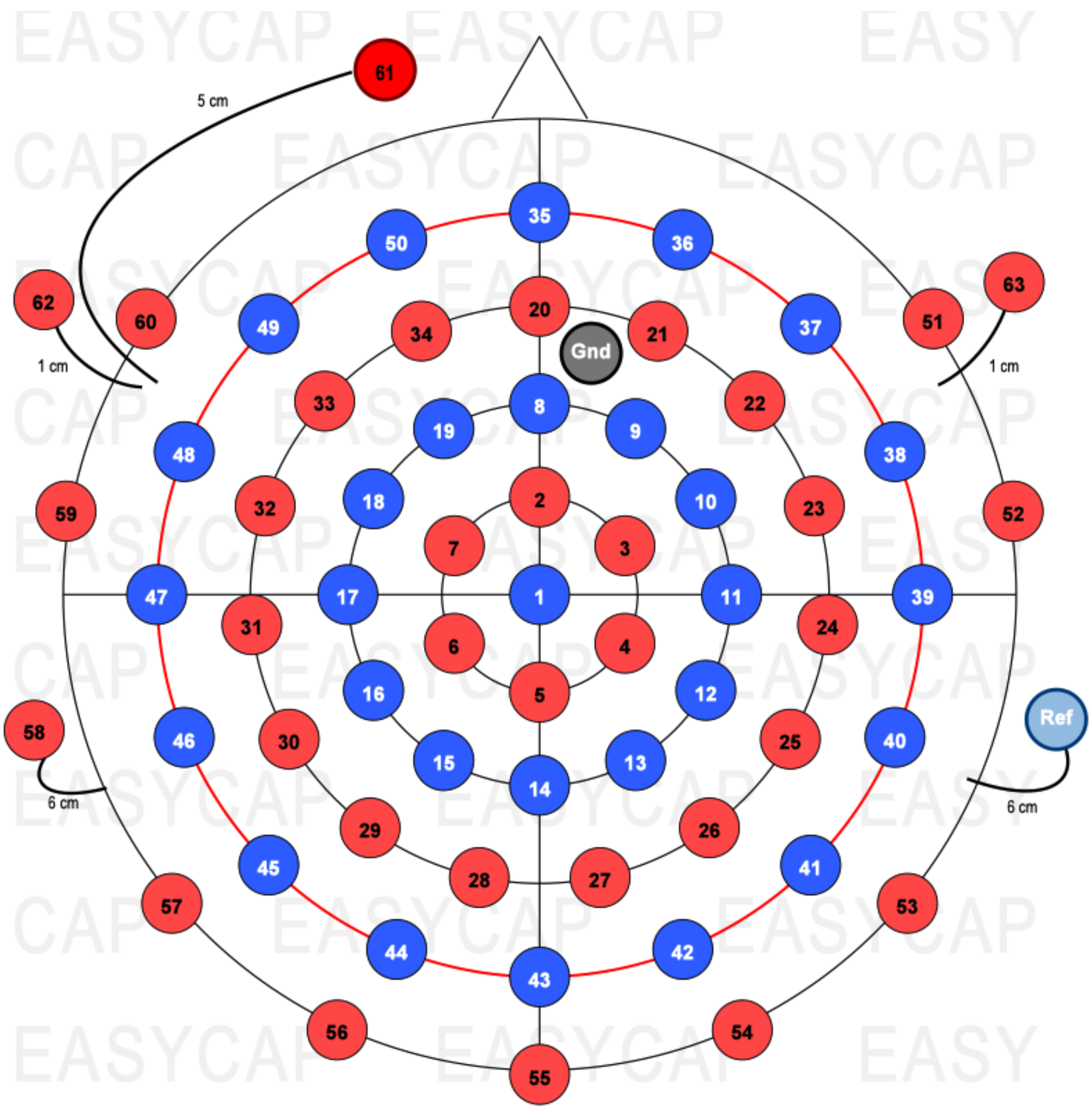

Figure 2: Diagram for electrode positions in a typical 64-channel cap.

2.5 ERP Data

The three lateralized, large-amplitude preparatory ERP components previously reported to be associated with attentional control between cues and targets (Early Directing Attention Negativity, Anterior Directing Attention Negativity, Lateral Directing Attention Positivity) were measured as the difference between electrodes contralateral and ipsilateral to the cued target location (Lasaponanra et al., 2018). During the first series of analysis, each component was analyzed within their conventional region of interests (ROIs) and time windows (Kelly et al., 2010; Lasaponanra et al., 2018): EDAN (240-420 ms post-cue, posterior left & right), ADAN (300-700 ms post-cue, frontal left & right), LDAP (400-800 ms post-cue, posterior left & right). In general, I compared each averaged waveform from the 8 conditions (2 visibility x 2 congruency x 2 attended locations) at electrode sites ipsilateral and contralateral to the direction of the cued attention shift. The components were isolated following the steps by Kelly and colleagues (2010). First, electrodes from each averaged ERP were re-labelled to either contralateral or ipsilateral to the cued location. For example, an electrode site 15 (Fig.2, showing the 64-channel electrode cap arrangement) over the left hemisphere was renamed as contralateral in condition where the cue indicated a rightward shifting, and as ipsilateral in condition where the cue indicated a leftward shifting. From these re-labelled channels a contralateral waveform (average of rightward attention shifting for the left hemisphere and leftward attention shifting for the right hemisphere) and an ipsilateral waveform (average of leftward attention shifting for the left hemisphere and rightward attention shifting for the right hemisphere) were created. The three lateralized components were then isolated from the difference between these contralateral and ipsilateral waveforms (Luck, 2012). EDAN and ADAN are expressed as more negative voltage at the contralateral side compared to ipsilateral side, whereas the LDAP is a more positive voltage at the contralateral side compared to the ipsilateral side.

Chapter 3: Results

3.1 Priming Effect on Task Performance

Reaction times (RTs), computed as the time interval from the target onset to when a response was made, were averaged for correct responses and were analyzed with a repeated-measures ANOVA for congruency x awareness factors. RTs for each of the four conditions are shown in Fig 3. In general, no significant difference was found between congruent trials and incongruent trials, F(1, 14) = 4.025, p= 0.065. RTs also did not differ significantly between aware or unaware conditions, F(1,14) = 0.340, p = 0.569. In addition, no significant congruency x awareness interaction was found, F(1,14) = 1.604, p = 0.226.

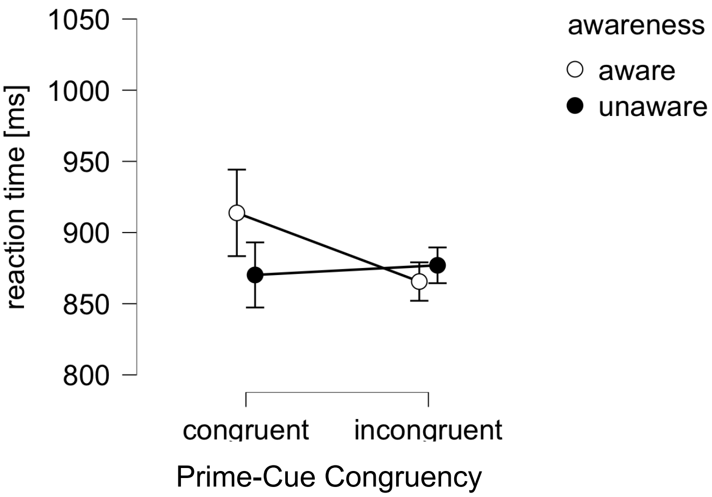

Figure 3: Averaged Reaction time in ms for each of the four conditions.

3.2 Conventional lateralized cue-ERP activity

To investigate the attention control process prior to target onset, we examined a series of ERPs after the symbolic visual cues onset. The general morphologies of the ERPs were similar across four conditions, including a negative displacement contralateral to the cued location at frontal-central electrode sites at 300-700ms (ADAN), followed by a positive displacement contralateral to the to-be-attended location at posterior scalp sites around 400-800ms. Traditional cue-ERPs also include the analysis of EDAN, a contralateral negativity at posterior scalp sites that precedes the onset of ADAN. The time window (240-400ms post-cue) and the location (posterior electrodes) of a typical EDAN was examined, but no contralateral to ipsilateral polarity difference was found at the expected latency or location. Thus, the main analysis in this section focuses on the amplitude and the latency of the ADAN and theLDAP, while the EDAN component was not included in further analysis.

3.2.1 ADAN

Fig. 4 shows the lateralization of the preparatory ERP over frontal-central sites contralateral and ipsilateral to the attentional shift according to the cue. The mean amplitude from five frontal-central electrodes at 300-700ms post-cue window was calculated separately for each condition for each subject and underwent paired t-tests. ADAN emerged at frontal and central electrode sites and its polarity aligned with the position of the relevant cue: In the aware congruent condition, there was a statistically significant negativity contralateral to the cued location as compared to the ipsilateral side, $t(14) = -4.730$, $p<0.001$, as well as in the aware incongruent condition, $t(14) = -4.44$,

$p<0.001$. Similarly, a statistically significant negativity was observed in the unaware congruent condition, $t(14) = -3.496$, $p=0.002$. However, in the incongruent unaware condition, the negativity at the contralateral side compared to the ipsilateral side was much smaller and did not reach statistical significance, $t(14) = 0.466$, $p=0.323$.

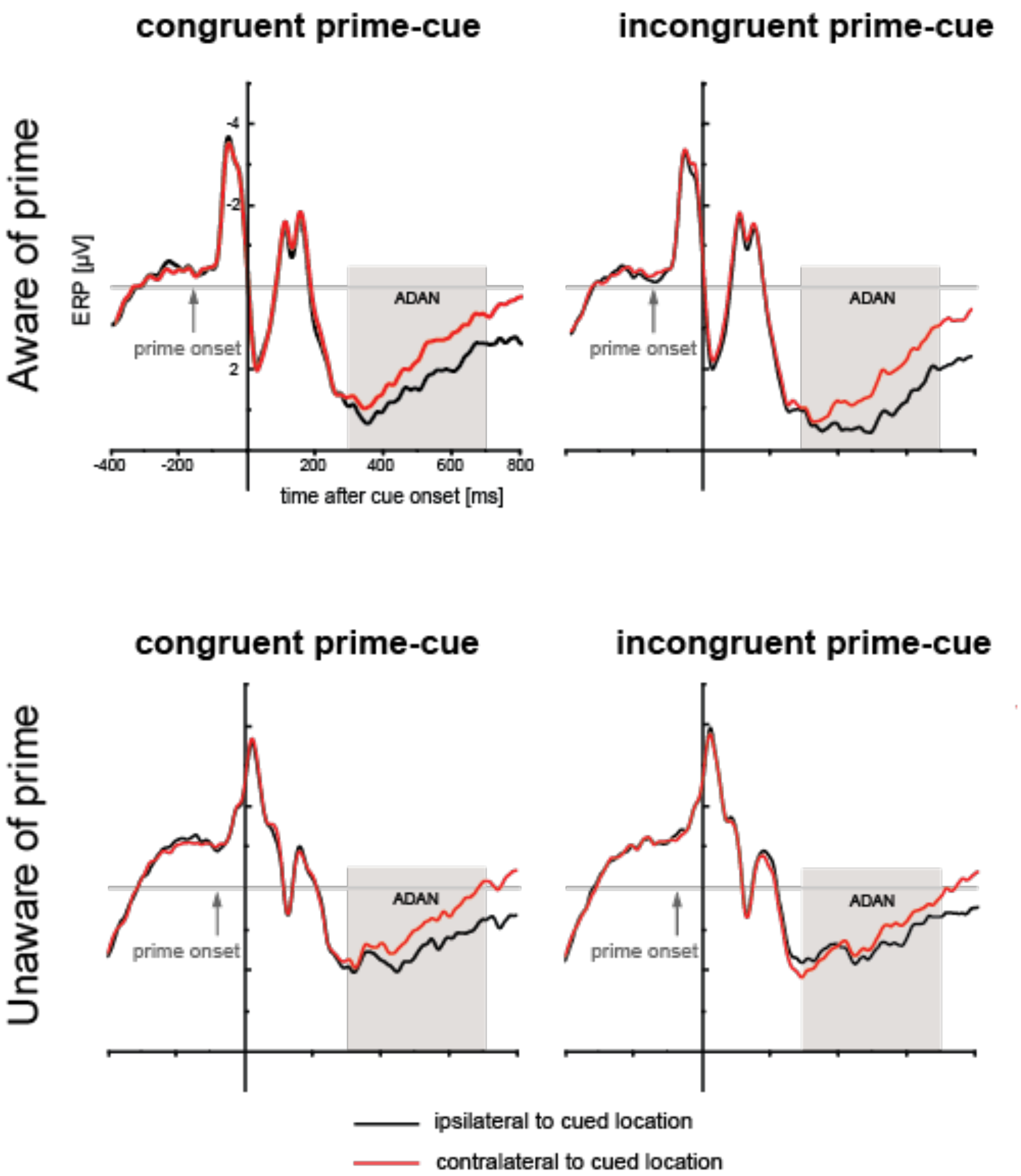
congruent prime-cue
incongruent prime-cue

Figure 4: Average ADAN ERP elicited at frontal-central electrodes (F9/F10, FT7/FT8, F7/F8, F5/F6, AF7/AF8). ADANs across four conditions are displayed for electrode sites contralateral and ipsilateral to the cued location.

3.2.2 LDAP

Fig. 5 shows the lateralization of the preparatory LDAP component over posterior electrode sites. The mean amplitude from four posterior electrodes at 400-800ms post-cue latency was calculated separately for each condition for each subject. Similar to the ADAN, the polarity of the LDAP aligned with the position of the relevant cue: in the aware condition, LDAP was significantly more positive contralateral to the cued location in both the congruent condition ($t(14) = 7.036$, $p<0.001$) and the incongruent condition ($t(14)= 4.471$, $p<0.001$). In the unaware condition, a similar lateralized positivity effect was observed in the congruent condition, $t(14)= 3.963$, $p<0.001$ and in the incongruent condition, $t(14) = 5.188$, $p<0.001$.

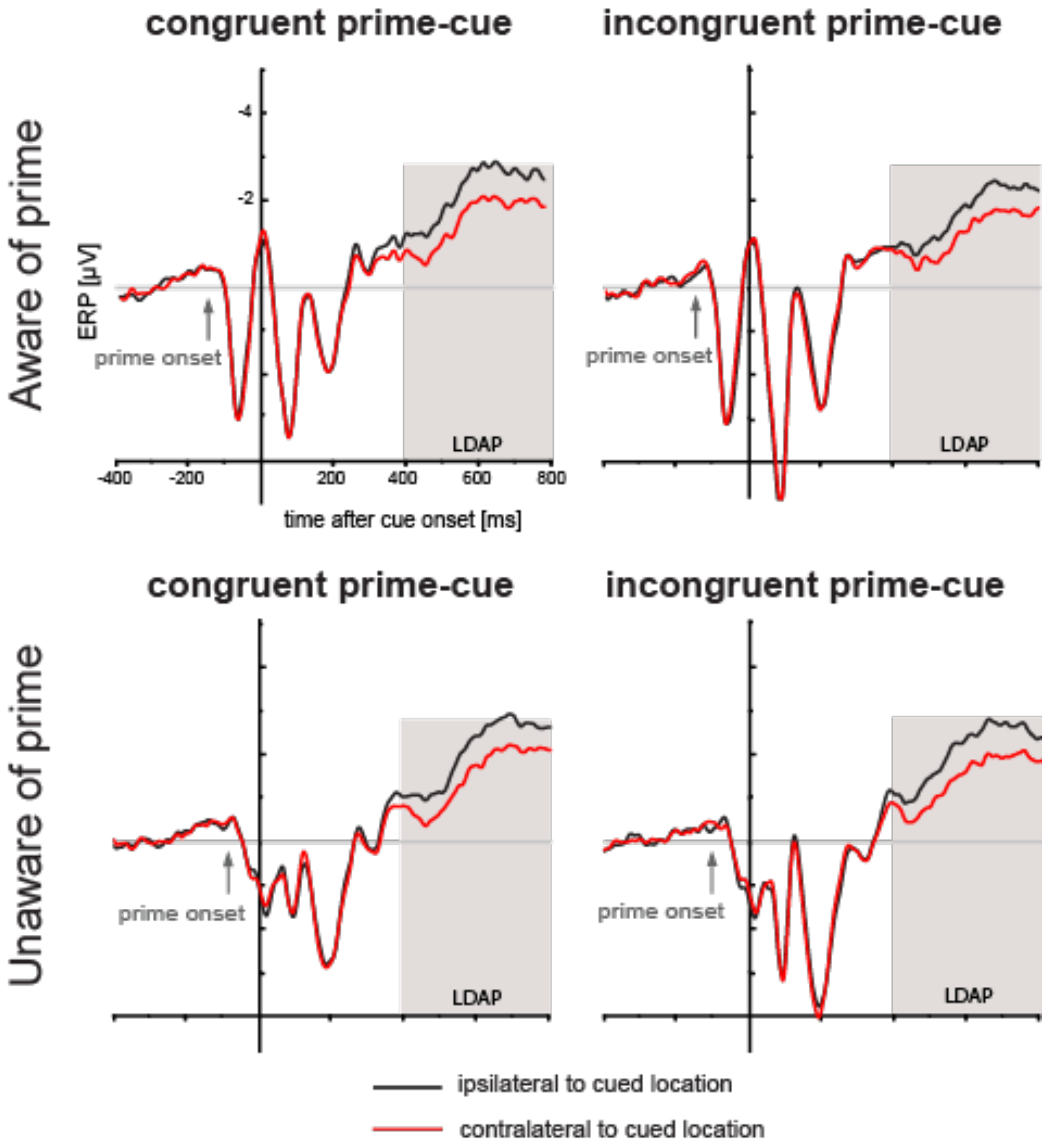

Figure 5: Average LDAP ERP waveforms elicited at posterior electrodes (O2/O1, O10/O9, PO10/PO9, P10/P9, PO8/PO7, P8/P7, P6/P5, P4/P3, PO4/PO3). LDAPs across four conditions are displayed for electrode sites contralateral and ipsilateral to the cued location.

3.3 Lateralized activity isolated for congruency x awareness comparison

Because of the different prime-cue interval between aware and unaware conditions, it is difficult to directly compare the preparatory ERPs between these conditions as their latency and amplitude will be affected by anything that happened prior to that. The solution I adopted here was to make a contra-minus-ipsi difference wave for each of the four conditions and then compare these difference waves. Because any sensory effects due to pre-cue activity across contralateral and ipsilateral electrode side within a condition should be the same, what remains in the difference waves should be solely reflective of the extent of spatial attention control related to the congruency*awareness manipulation (Luck, 2013).

3.3.1 Effect of prime-awareness on Anterior Directing Attention Negativity

The statistical analysis was carried out on the mean amplitude of the same frontal-central electrode sites as in the ERP amplitude analysis. Fig. 6 shows the four contra-minus-ipsi difference waves of each condition. The patterns resembled the finding from Fig. 4. The difference between waveforms extracted from contralateral and ipsilateral cued location was expressed as an upward (negative) trend starting around 250-300ms, similar across all four conditions. Interestingly, in the incongruent unaware condition, the contra-ipsi difference appeared to be positive from 200-400ms (Fig. 6), indicating the voltage at the ipsilateral side was more negative than the contralateral side. This negativity seems to propagate to the contralateral side after 400 ms post-cue. The reversal polarity is also illustrated in a topography map (Fig. 11), shown as a positive voltage at frontal-central electrode sites between 300-400 ms. This positive voltage is then replaced by a contralateral voltage after 400 ms at the same electrode sites.

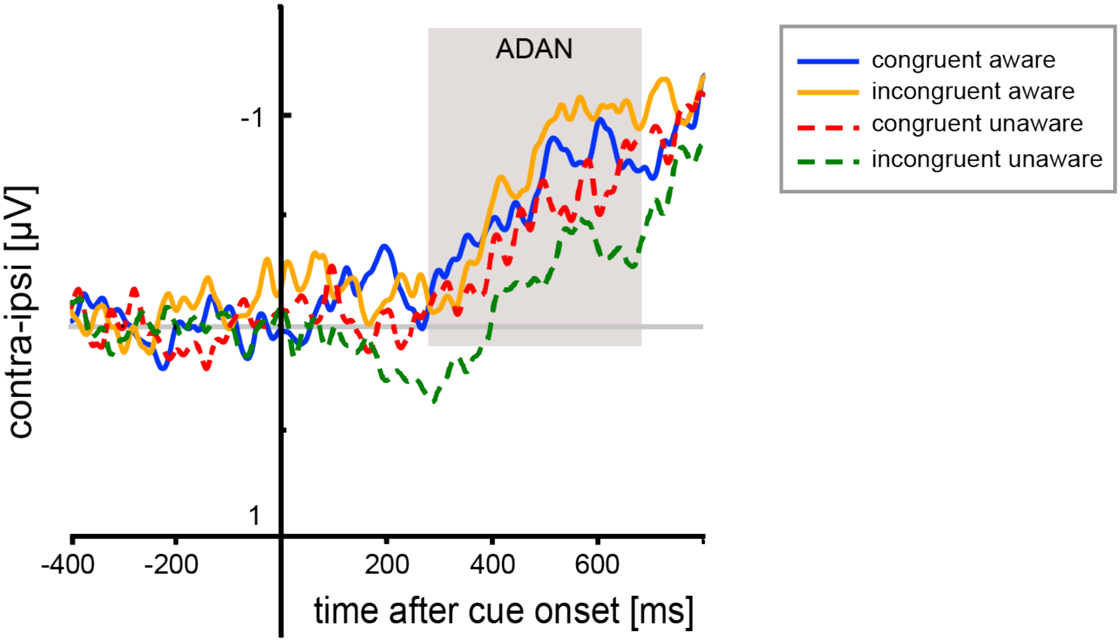

Figure 6: Difference waves displaying ADAN amplitude differences of four conditions.

To confirm this opposite polarity observation, a mass univariate analysis was performed, during which ERP difference wave amplitudes at every electrode and at every time point were tested again zero resulting in a heat-map of t-scores (Fig. 7), corrected for multiple comparisons via the false discovery rate (FDR) approach (Groppe et al., 2011). The greater the t-score, the more reliably the ERP amplitude to target and the standard differ. ADAN were shown as a negative t-value at anterior electrodes, present in the congruent aware, incongruent aware, congruent unaware condition, and absent in the incongruent unaware condition.

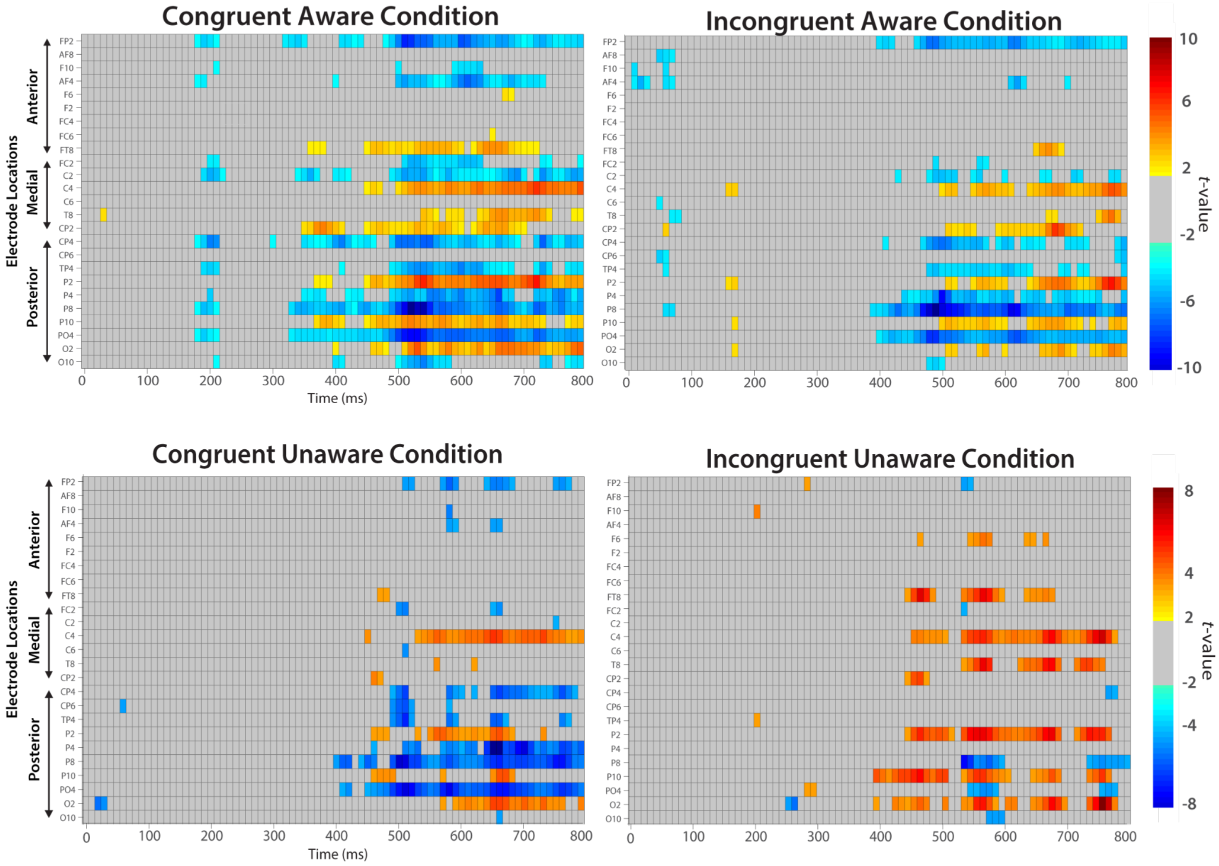

Figure 7: Mass univariate analyses diagrams for all four conditions illustrating significant differences between ERPs to targets and standards. Each individual electrode is plotted as a row on the y-axis, while time (ms) is plotted on the x-axis. Only significant t values (5% FDR) are plotted in the figure.

These observations were confirmed by subsequent repeated measures ANOVAs (Fig. 8), which showed significant statistical main effects of awareness (F(1, 14) = 18.376

p < 0.001), as well as a significant interaction effect between congruency and awareness, F(1, 14) = 6.530, p = 0.023. Subsequent post hoc tukey tests revealed that the ADAN component in the incongruent unaware condition was small in magnitude (i.e., statistically more positive) than the congruent aware condition (M = -0.422, SD = 0.414), t(14) = -3.752, p= 0.004, and incongruent aware condition (M= -0.564, SD = 0.393), t(14) = -4.455, p< 0.00., and was near statistically significantly reduced compared to the congruent unaware condition (M = -0.315, SD = 0.323), t(14) = -2.696, p = 0.054. ADAN in the incongruent unaware condition, measured across 300-700 ms, may have been reduced in magnitude because of an initial positive contra-ipsi difference in this condition during the beginning of this time-window (possibly reflecting a shift of spatial attention to the location indicated by the unseen prime).

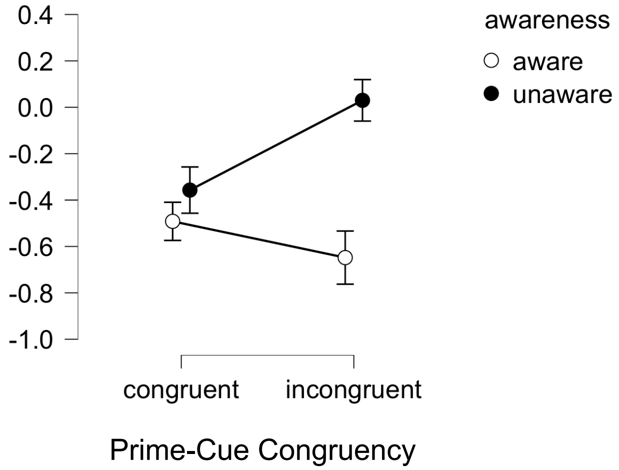

Figure 8: Descriptive plot showing the mean difference and variability on the amplitudes of ADAN components at 300-700ms post-cue in different conditions. Mean amplitude difference was computed as contralateral minus ipsilateral to the cued location. Error bar = MSE.

To confirm the initial positive contra-ipsi difference observed in the incongruent unaware condition (Fig. 6) was statistically significant, I divided the ADAN component into two time frames, 300-500ms (where the positive contra-ipsi difference was observed) and 500-700ms and conducted a repeated measures ANOVA test on each of the time frame. Consistent with this observation, there was a significant interaction effect of congruency*awareness, $F(1,14) = 5.870$, $p = 0.03$, in the early ADAN (300-500 ms) component. A subsequent post hoc Tukey test confirmed that the incongruent unaware condition ($M = 0.124$, $SD = 0.448$) was more positive than congruent aware ($M = -0.341$, $SD = 0.412$), congruent unaware ($M = -0.300$, $SD = 0.326$), and incongruent aware condition ($M = -0.443$, $SD = 0.388$). Furthermore, the ANOVA on the late ADAN (500-700ms) also revealed a significant interaction effect. The ADAN amplitude in the incongruent unaware condition ($M = -0.064$, $SD = 0.606$) was statistically significantly different from congruent aware condition ($M = -0.643$, $SD = 0.487$) and from incongruent aware condition ($M = -0.853$, $SD = 0.778$), but not from congruent unaware condition ($M = -0.414$, $SD = 0.575$). These late-window ADAN differences were possibly due to the delayed latency of the contralateral negativity in the incongruent unaware condition.

3.3.2 Prime-awareness on Lateral Directing Attention Positivity

The statistical analysis was carried out on the mean amplitude of the same posterior electrode sites as in the LDAP amplitude analysis. As shown on Figure 9, the patterns of contra-minus-ipsi difference waves resembled the LDAP findings from Figure 5. The difference between waveforms extracted from contralateral and ipsilateral cued location was expressed as a downward (positive) trend starting around 400ms, similar across all four conditions. The posterior positivity is further illustrated in the topography mapping in Figure 11. A subsequent repeated measures ANOVA (Fig. 10) confirmed the observation, in which no significant main effects of congruency ($F(1,14) = 0.896$, $p = 0.360$) or awareness ($F(1,14)= 0.059$, $p = 0.812$) were observed. There was no significant interaction effect between congruency and awareness manipulation $F(1,14) = 2.611$, $p = 0.128$.

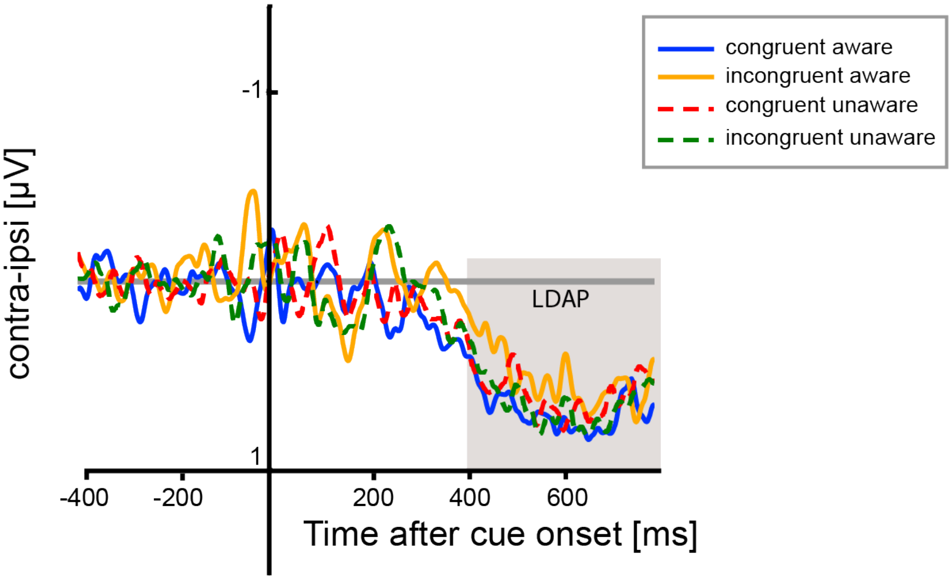

Figure 9: Difference waves displaying LDAP amplitude differences of four conditions.

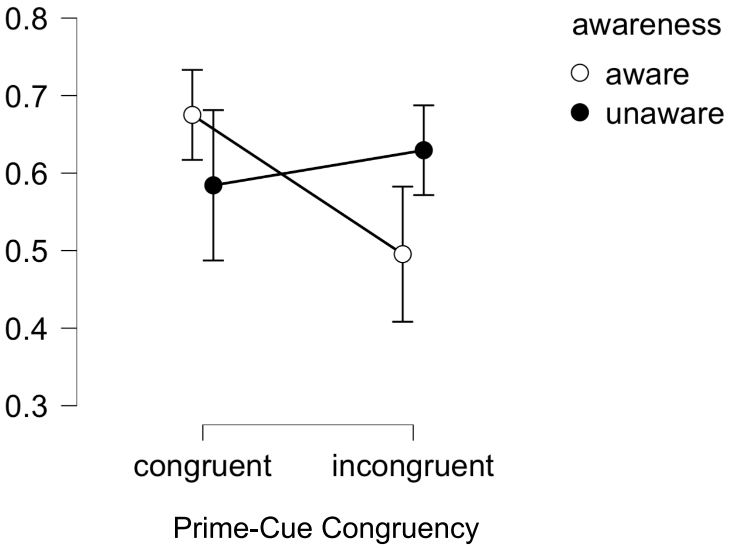

Figure 10: Descriptive plot showing the mean difference and variability on the amplitudes of LDAP components in different conditions. Mean amplitude difference was computed as contralateral minus ipsilateral to the cued location. Error bar = MSE.

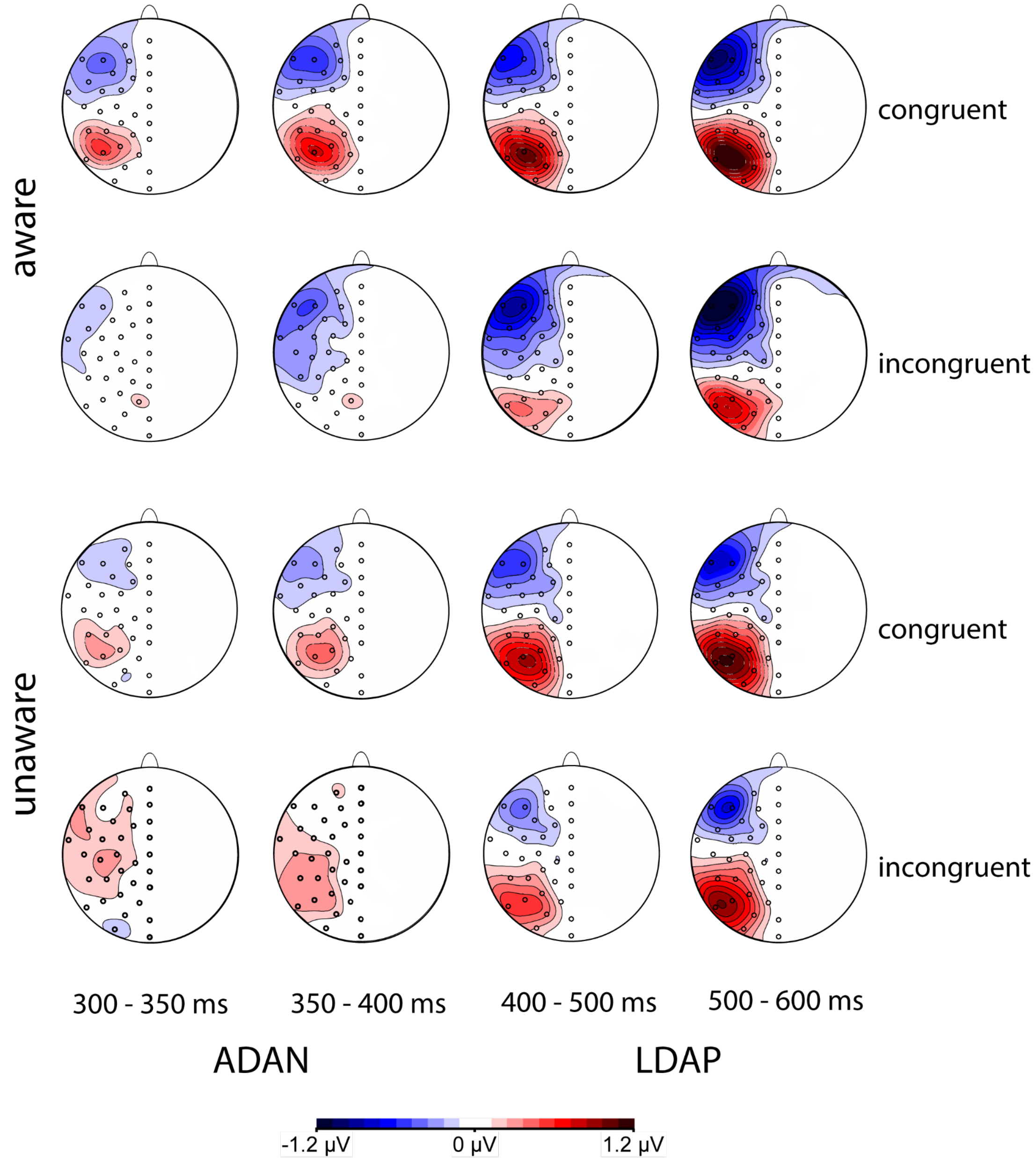

Figure 11: Topography maps depict hemispheric differences (contralateral minus ipsilateral to cue direction) on the left side of the scalp for time windows that show significant lateralized ADAN and LDAP amplitudes from four conditions. ADAN is divided into two windows for display, 300-350ms, 350-400ms post-cue. LDAP is divided into two windows for display, 400-500ms, 500-600ms.

Chapter 4: Discussion

The present study examined the effect of subliminally presented visual prime on the executive control of spatial covert attention. Subjects were presented with a spatial cueing task with a symbolically meaningful cue entailing the to-be-attended location; a prime that contains symbolically congruent or incongruent information to the cue was presented before the cueing task, with its visibility controlled by a metacontrast masking procedure. The brain activity related to attention control was examined during the cue-target interval. The current experiment provided some interesting evidence on the relationship between visual awareness and attention control: in the invisible incongruent prime condition, we observed a delay and a polarity-reversal of the ADAN component, while no priming effect was reflected on the LDAP component or in behavioral performance. This is generally in line with our hypothesis that attention control can not operate normally when the task-irrelevant distractor is outside of conscious perception. However, the reversal polarity of ADAN only in the incongruent unaware condition is a novel finding and is subject to various interpretations, as discussed below.

4.1 Behavioral Performance

Previous masked priming experiments often took reaction time as a main measurement for the visuomotor priming effect. Specifically, an incongruent prime delays the responding to the target while a congruent prime propels responding to the target (Ansorge et al., 2014; Palmer & Mattler, 2013), an observation termed congruency effect. Furthermore, a congruent prime, even when rendered invisible, can help to improve the speed of an accurate response (Lau and Passingham, 2007; Palmer & Mattler, 2013).

The current study found no priming effect on the reaction time of the attention shifting task. This result is actually consistent with previous research, which found that the congruency effect increases inversely with the time interval between prime and target onset, namely stimulus onset asynchrony (SOA). In other words, the longer the SOA between the prime and the target, the smaller the congruency effect. In fact, the original study by Palmer & Mattler (2013) found that a prime-target SOA of 170ms could successfully induce a priming effect, measured by the reaction time and accuracy to the target. In contrast, the prime-target SOA in the current study was expanded to approximately 900ms for the purposes of observing EEG waveforms in the time period between the cue and the target. Such a large SOA may cause the short-lived effect of the prime to be minimally influential when the target appeared 900ms after the prime, which explains why there were no behavioral differences across four conditions. Again, this is expected, as I briefly mentioned in the Introduction chapter: the purpose of the current experiment was to look at the process of executive attention control in the brain when presented with conflicting or consistent information with the current task, NOT the behavioral outcome of visuomotor priming.

4.2 Lateralized-ERP activity in cue-target interval

First, as a confirmatory finding, we observed ADAN and LDAP components in all four conditions, with a time window and topography distribution consistent with previous research (McDonald & Green, 2008; Van Velzen et al., 2006). No EDAN component was found when comparing the voltages from contralateral to ipsilateral occipital sites. EDAN is likely to mark the early attention selection of feature processing of the cue stimulus (McDonald and Green, 2008), and thereby is generally observed in the 240-420 ms time window post-cue. For example, a lateralized EDAN in response to an arrow cue likely means that the subjects are attending to the arrowhead, which is also lateralized, when interpreting the symbolic information of the cue (only a portion of the arrow cue is informative). A likely explanation of the null EDAN finding in the current study is that a symmetrical cue was used, as opposed to an arrow cue. When interpreting the location information entailed by the cue, the subjects attended to the whole contour of the cue, rather than a portion of it. As a result, no lateralized EDAN was found.

4.2.1 On the source of Anterior Directing Attention Negativity

The present study revealed a novel pattern of results regarding how the lateralization of the ADAN was affected by congruency and awareness of the prime. Specifically, in the incongruent unaware condition (invisible prime providing incongruent information to the cue), during early time periods in the ADAN window at the frontal scalp, there appeared to be a more negative voltage at the ipsilateral electrode site compared to the contralateral site. This was opposite to the typical topographical distribution of ADAN component, which was supposed to be a more negative voltage contralateral to the cued location compared to the ipsilateral side. In the current experiment, the contralateral negative voltage in the incongruent unaware condition was not observed until 400ms after cue-onset.

Interestingly, this initial ipsilateral negativity and the delay in the contralateral negativity was not observed when the incongruent prime was visible. A number of spatial cueing studies found a delayed ADAN when the cue was incongruent, which they interpreted as the brain requiring more time to process the conflicting information. The null finding of ADAN delay in the incongruent aware condition could be explained by the use of different types of cues and primes in the current study. Most of the spatial cueing research uses arrow-cues, pointing left or right to instruct subjects to attend to one side or the other. What's special about an arrow's shape is that it can trigger at least partly automatic orienting to the pointed location (Jongen et al., 2007). Conversely, the diamond/square shape requires subjects to learn the symbolic association between its shape and associated direction, making the relationship more top-down driven and less automatic. The ADAN component found in previous research using arrow cues is possibly automatically triggered and has an earlier onset. But in the incongruent cueing condition, this automatic process has to be overruled and rectified for correctly orienting of attention. Thus, the shift of attention as reflected by ADAN might be delayed. In the current study, the shifting of attention to the correct location requires top-down control anyway, thus less susceptible to automatic processing of the stimulus.

Some might argue that the observed ADAN could be related to physical differences between conditions. In other words, the reason for a reversal polarity in early ADAN might be purely due to the special sequence of stimulus presentations in the incongruent unaware condition. Indeed, each of the four conditions differed slightly by either their prime-cue time interval or the prime-cue shapes. It is thereby difficult to dissociate the physical differences between conditions from observed brain waveform discrepancies. Nevertheless, to reduce stimulus-related confounds, we included an equal number of trials of square and diamond to counterbalance the direction of attention shift. For the analysis, we collapsed leftward and rightward shifting trials together for every condition; the data comparison was always between brain activity contralateral and ipsilateral to the cued location. Thus, the observed priming effect cannot be due to any location-related or stimulus-related differences.

It is also unlikely that ADAN activity is modulated by bottom-up attention. First, the time window for an exogenous, stimulus-driven attention should be a lot earlier, as it is automatically triggered by the stimulus presentation. The EDAN component, thought to reflect interpretation of the location information of the cue and was somewhat top-down regulated, has an onset around 200ms. Automatic triggering of involuntary attention should be even earlier than that. Second, if ADAN is at least partly modulated by an involuntary process, the amplitude and the latency of ADAN should not differ across aware and unaware conditions. An involuntary process means it can operate outside of consciousness, thus ADAN should not be affected by the visibility manipulation, which is clearly not the case in the current study. Thus, we can confirm that ADAN is an indicator of attention control mechanisms or some attention-related cognitive processes.

Since the polarity of ADAN is always more negative at contralateral side to the cued location, the initial contralateral positivity in the incongruent unaware condition could mean that the brain was initiating selection processes at the location indicated by the incongruent prime, which was opposite of the correct cued location (i.e., a contralateral negativity to the prime, not the cue). This incorrect orienting of attention was subsequently corrected, once the brain had enough time to process the cue and inhibit the effect of the prime, which would explain the slightly delayed onset of the negative polarity at contralateral cued side (Fig 6). On the contrary, in the incongruent aware condition, the visible prime failed to perturb the spatial attention orienting to the cued location, presumably because there was enough time for cognitive control mechanisms to deal with the conflicting prime-cue information, both of which were consciously seen, prior to the initiation of the spatial selection process. This interpretation is consistent with the working hypothesis that consciousness is required for cognitive control, such that an invisible prime would be outside of this control and may influence subsequent processing stages (Naccache, Blandin, & Dehaene, 2002)

Previous research has localized the source of ADAN activity in the premotor cortex. Thus, another promising interpretation links ADAN with saccade-related activity in the frontal eye fields (FEF). Van der Lubbe et al. (2006) compared the amplitude of ADAN in two tasks, a choice-response task with no horizontal eye-movement involved and a saccade task in which subjects gazed towards a cued location. They observed a more pronounced ADAN in the saccade task and nearly absent in the choice-response task. From this observation they concluded that ADAN is related to saccade preparation and less to attentional orienting. What's interesting about their study is that they also found an anterior positivity shortly preceding a saccade, which they denoted as an anterior saccade direction-related positivity (ASDP). Both ADAN and ASDP arose from FEF, as source analysis revealed. The researchers speculated that the negativity reflects saccadic inhibition, whereas the positivity entails saccadic activation. Saccadic inhibition originates from the task instruction of fixating eyes at the center, which requires the subjects to inhibit their natural tendency to shift their eye gaze towards the attended location (Mathews, et al., 2006).

Relating back to the current study, the reversed anterior polarity observed in the incongruent unaware condition could possibly be explained by saccadic inhibition and activation. An anterior positivity at an early time window of 200-400ms might entail an involuntary activation of saccade to the location indicated by the prime. This is possible if the brain was only trained according to the task instruction, that is, to inhibit saccades in response to the cue. Thus, when an unexpected prime that offered conflicting spatial information, a saccade preparation was activated. Further, this saccadic activation was absent in the visible incongruent prime condition. A possible explanation could be that a visible prime would allow the brain to recognize its task-irrelevance and block any related activations. In the invisible prime condition, however, a successful pre-motor control could not be initiated successfully, thereby resulting in the initial anterior positivity. The control mechanism of pre-motor activity is arguably closely linked to the neural substrates that give rise to spatial attention control; advocates of the premotor theory of attention propose that the two use the same neural substrates. While different in the purported underlying mechanism, this interpretation would still align with my hypothesis that the executive attentional control would be impaired in response to an invisible distractor.

Most recently, Meyberg et al., (2017) proposed ADAN as a microsaccade-related corneoretinal artifact. They developed a complex algorithm based on Independent Component Analysis (ICA) to decompose the continuous brain waveforms into independent components representing neural activity and artifacts. Their special ICA algorithm was trained to detect microsaccades and correct them. By employing a simple spatial cueing design, they found an ADAN-like negativity at frontal electrodes that disappeared after ICA-corrected. They concluded that the frontal ADAN was due to small corneoretinal artifacts that traditional ICA and standard artifact rejection procedures have failed to correct. Nonetheless, they observed a reliable ADAN at central sites irrespective of the correction procedure. This might suggest that the central part of the ADAN is not an oculomotor artifact but indeed be related to supra modal attentional control, suppression of saccade towards the cued location, or holding the location profile in working memory. Further, this central ADAN was delayed when cue was incongruent. To our knowledge, this is the first study that argues for an anterior negativity at both frontal and central sites. Thus, it is possible that the central ADAN is due to an imperfect ICA algorithm that fails to correct premotor activity at central electrodes. In the current study, the ADAN was observed in mostly frontal electrodes and no central ADAN was found. Nevertheless, it is possible that ADAN is related to microsaccade activity. If so, the reversal ADAN in the current study entails that the subjects were making involuntary microsaacade to the location indicated by the incongruent prime. This interpretation is still in line with our hypothesis, as the microsaccade to the wrong location was successfully inhibited in the incongruent aware condition.

It is likely that ADAN is generated by processes involved in the deployment of attention to the attended side. Because it's a relatively earlier time course compared to the LDAP, and its spatial distribution on the scalp, researchers have speculated the onset of ADAN might reflect the initiation of attentional control in the frontal cortex. If this hypothesis holds true, the delayed onset of ADAN in the incongruent unaware condition, but not in the incongruent aware condition, may indicate that the brain requires more cognitive resources and thus more time to handle the conflicting information from the prime. If the anterior negativity is reflective of a successful initiation of attention control network, the contralateral positivity in the incongruent unaware might signal an impaired control model. To conclude, while there is room for debate on the underlying mechanism of ADAN, the current results demonstrated that spatial attention control is likely to be disrupted when the incongruent prime is rendered invisible.

4.2.2 No Priming Effect on Lateral Directing Attention Negativity

The LDAP has not received as much controversy regarding its sources and underlying mechanisms. It has been considered to reflect the preparatory selective processing of the to-be-attended location, setting up for the subsequent task-related stimulus processing (McDonald & Green, 2008), and the deployment and sustaining of attention at the cued location. Previous research using similar spatial cueing paradigms often found a delayed LDAP in the incongruent condition and has been linked to the difficulty in solving the inconsistency and encoding directional information for a correct attentional shift in incongruent prime-cue condition (Jongen et al., 2007; Meyberg et a., 2017). It is considered to be an indicator for a top-down control of attention.

Contrary to many previous results, but not surprisingly, we found no priming effect on the amplitude or latency of the LDAP. It seems that the onset of LDAP was slightly delayed in the incongruent aware condition, as shown on topographic maps (Fig. 11) and the contra-ipsi difference waves (Fig. 9), though this observation is not supported by statistical analysis. The null finding of LDAP is consistent with both the behavioral performance from the current task and the original priming study by Palmer &Mattler (2013). LDAP reflects the successful anticipatory orienting of spatial attention to the correct location; thereby, the experiment showed that the prime, whether invisible or visible, congruent or incongruent with the cue, did not affect the correct deployment of attention. This interpretation is consistent with the null finding from measuring reaction time across four conditions, confirming that the prime does not affect the outcome of attention orienting.

4.3 Theoretical Implications of the Subliminal Priming Effect

The current study confirmed the hypothesis that a task-irrelevant distractor, when rendered invisible, causes greater disruptive effect to the attention control mechanism at play, possibly due to a failure to establish inhibitory control over the task-irrelevant signals. This finding aligns with the previous research by Tsushima and colleagues (2006), who found that a distracting motion signal, when presented subliminally, caused higher visual cortex activation but lower lateral prefrontal cortex activation. They interpreted the results as reflecting a bidirectional interaction between the visual system and the cognitive control system: subthreshold signals might be processed sufficiently by the visual system, but are not strong enough to trigger response from the cognitive control system. In the current study, however, we observed a different pattern of neural responses to the distractor. Specifically, we found a reversal in polarity of the ADAN component, possibly indicating the brain has interpreted the location information entailed by the incongruent prime and has initiated preparatory orienting to location indicated by the prime. What's more, there were no enhanced or attenuated electrophysiological signals observed, inconsistent with the fMRI result from Tsushima and colleagues (2016). It is likely that different brian imaging techniques would yield different observations: the high spatial resolution of fMRI allows it to capture nuanced neural activations at deeper cortical levels whose electrical signals are not strong enough to travel to the scalp and captured by EEG. The advantage of spatial resolution comes with the cost of poor temporal resolution, making it difficult for fMRI to measure the exact transient neural dynamics occurring at microscopic time scales. On the contrary, EEG was able to detect the transient neural signals that reflect stages of cognitive processes, but at the cost of poor spatial resolution, making it difficult to localize the sources of the neural activations. Alternatively, it is possible that the control system responsible for distractor inhibition was a different one compared to the system at play during the motion distractor paradigm by Tsushima and colleagues.

Another important theoretical implication of the current study is that it provides empirical support for the Attention Schema Theory (AST). AST proposes that subjective awareness *is* the brains' control model of endogenous attention. Thus, if there is no subjective awareness of the prime, the control model for endogenous attention will be impaired, leading to a failure to inhibit distractor prime information and to facilitate accurate spatial attention orienting. Evidence for the existence of such predictive control models mainly came from fMRI studies (Wilterson et al., 2021). Specifically, the right temporalparietal junction (TPJ), a region hypothesized to be the hotspot for the predictive control model of attention, was activated when a visible cue was not predictive of the target location, but was not active when the non predictive cue was invisible. Meanwhile, there was an overall enhanced activity at the left angular gyrus and the medial prefrontal cortex following the non-predictive cues compared to the predictive cues, regardless of the cue awareness manipulation. Thus, the non-predictive invisible cues were processed, but didn't reach the rTPJ. The researchers concluded that the rTPJ activation triggered by the visible non-predictive cue was due to a transient violation of a continually computed predictive model of attention control. Conversely, the current study did find a different pattern of brain activity triggered by an invisible, incongruent prime, but failed to find differential neural signals in response to a visible incongruent prime. However, our finding didn't necessarily contradict with the results from Wilterson et al., (2021). The enhanced activation of rTPJ in response to a visible distractor reflected how attention control was successfully implemented - the control model was functioning properly, recognizing the conflicting information and inhibiting further processing. No rTPJ activation in response to the invisible distractor indicated that the distractor escaped the control model of attention. As a result, endogenous attention was affected by the distractor, consistent with the implication of the reversal polarity of the ADAN observed in the current study. Alternatively, the disparate brain activation patterns could be solely due to the differences in the design which triggered a different attention control model.

In summary, the current study was in general consistent with the hypothesis by the AST: when a distractor or a conflicting information is presented subliminally, the brain could not facilitate effective attention control to inhibit it.

4.4 Strengths, Limitations, and Future Directions

Very few studies have examined the brain activity signaling the attention control process underlying a subliminal priming experiment. Most of the priming studies either focus their analysis on the behavioral performance, or are mainly interested in the period after target presentation. The current study is the first to use the ERP technique to investigate how spatial attention control can be affected by invisible task irrelevant information, by comparing the brain waveforms signaling preparatory orienting process. Focusing on the brain activity in the cue-target period potentially eliminates confounds related target processing or post-perceptual processes and allows results to be reflective of a neat attention control sequence. Another strength of the study is the use of the Quest algorithm to find an individual threshold that renders the shape of the prime invisible. A number of studies looking at subliminal priming suffer from the critique that the subjective report of the stimulus awareness is often above chance level. Adjusting the metacontrast masking strength to individual threshold offers a nice fix to the issue, and we can confidently conclude that the difference observed between aware and unaware conditions was due to our visibility manipulation. In general, the current study adds evidence to the relationship between cognitive control and visual awareness, by illustrating that the spatial attention control mechanism is impaired to visual stimuli that are inaccessible to conscious perception.

Nevertheless, the present study also has several limitations. First, including a control condition during which the prime and the cue signal the subject not to shift attention to either side would be ideal. If so, I would be able to use the brain activity from this neutral trial as a baseline for statistical comparison. Having such a condition would allow us to better determine the EEG activity pattern related to stimulus processing so that we could subtract it from the main analysis. Although the current results would not be overruled by not having a neutral condition, this little addition would make the data cleaner and more persuasive.

Another design-related limitation is that only horizontal shifting cues were used in the study. Including conditions in which attention is oriented to non lateralized location would allow us to determine whether the cue-ERPs reflect location-related attention processes or an attention control network independent of laterality.

The current experiment opens up many exciting possibilities for future research. Future studies should further examine the specific mechanisms underlying the ADAN component and its exact association with the attention control network. A possible direction is the use of prime-cue from different sensory modalities, such as the auditory domain. Examining the attention control mechanism modulated by auditory-visual prime-cue would allow us to explore whether ADAN is modality-specific, or is indicating a supra-modal attention control network.

Another interesting line of research would be looking at the spatial-temporal neural dynamics modulated by subliminal priming. Neural oscillation is an exciting yet relatively new line of research, because it reflects bottom-up and top-down cognitive processes by allowing short-range or long-distance communication between neuronal networks, ensuring complex and integrative functioning (Cebolla & Cheron, 2019). Recent evidence has found that alpha-band oscillation, the dominant oscillation observed in the brain, is closely linked to the suppression and selection of attention process (Klimesch, 2012). Time-frequency analysis is undoubtedly a key analysis to perform once more data is collected on the current study, and it would be exciting to see if alpha oscillations, or other activity at different frequency-bands, shows subliminal priming effect.

4.5 Conclusion

The current study adds novel evidence to the literature by electrophysiological signatures of a disrupted spatial attention control system in response to a subliminal visual distractor. The disrupting ability of the prime is relatively weak and transient, affecting only the earlier stages of attention control. The study provided support for the Attention Schema Theory by showing that the brain failed to facilitate effective attention control to inhibit a distractor when it was presented subliminally.

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