AN ABSTRACT OF THE THESIS OF

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The present study examined whether attention capture is driven by object saliency or contingent on top-down control setting using a go/no-go paradigm. Specifically, we investigated whether salient color singletons capture attention only when the target itself is also a singleton. We used a go/no-go task. Participants were told to search the target display for a letter in a specific color and indicate its identity if it was present ("go" trials) and withheld their response if it was absent ("no go" trials). On every trial, this target display was preceded by a non-informative cue display containing a color singleton. The key manipulation was whether this irrelevant singleton contained the target color. We used the N2pc effect as a measure of attentional allocation. N2pc effects were obtained for all color singletons in the cue displays, even those that did not have the target color. This even held when we switched to a non-singleton target display (Experiments 4-5), suggesting capture based on stimulus salience. Intriguingly, whereas the robust N2pc effects indicated capture by salient stimuli, behavioral effects on response time suggested the opposite conclusion. These findings suggest that the irrelevant color singletons captured attention only briefly, releasing attention before the target arrived.

Keywords: Attention capture, singleton, No-go, N2pc

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An Electrophysiological Study of Involuntary Attention Capture in a Go/No-go Paradigm

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Nathan D. Herdener, Author

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This thesis is dedicated to Marie, Chet and in memory of the kind and loving Edna Britten. Your generosity is an inspiration.

INTRODUCTION

Significance

The allocation of spatial attention is a vital process that lies at the foundation of identifying and interpreting our current surroundings. While the scanning of the environment is a relatively effortless and unconscious process, there is a common experience of voluntary control over the direction of our 'mind's eye'. At the same time we often refer to something surprising as catching our attention 'out of the corner of our eye', belying another common experience of involuntary capture of spatial attention by some unexpected or salient stimuli. Though the shifting focus of the mind's eye is an almost ever present experience, there is still much to be understood about the underlying mechanisms of its control. Several decades ago, Posner (1980) made the distinction of two unique modes of attention, which he called *endogenous* and *exogenous* (also see e.g., Bundesen, 1990; Cave & Wolf, 1990; Duncan & Humphreys, 1989). Endogenous attention refers to the voluntary direction of attention and is also referred to as top-down or goal-driven control of attention. Exogenous attention is the involuntary capture of attention by new stimuli or changes in stimuli and is referred to as bottom-up or stimulus-driven allocation of attention. An example of endogenous control of attention is visually searching your kitchen table because it is a likely spot that you placed your car keys. On the flip side, we should expect to have the flashing lights of police car capture your attention completely exogenously regardless of whether or not you are looking for anything blue, red or flashing.

While there is little disagreement about purely endogenous control of attention, there is an ongoing debate in the field regarding the processing mechanism(s) driving the involuntary capture of attention (i.e., the exogenous component). It is argued that exogenous attention is not entirely separate from endogenous direction, since there appears to be a capacity for goals to create an affinity for a select feature or group of features. An everyday example of this would be looking for your car in a large parking lot and having your attention exogenously drawn to vehicles of similar model or color since it matches what your goal of finding your car. In order to explore the intricacies of this phenomenon researchers have sought to more accurately control the presentation of stimulus in a laboratory setting. Out of this research has emerged an extraordinary controversy between the claim that involuntary attention capture is driven purely by stimulus salience, regardless of the relevance of the stimulus to current goals, and the claim that our goals and motivation can influence the early stages of our attentional allocation process. Involuntary attention capture has been prominently supported with the use of a *singleton* stimulus, an object that is unique from a homogenous background in at least one dimension, such as color, shape or luminance. There have been some persuasive studies that argue that such salient stimuli have the inherent capacity to capture spatial attention (known as the *stimulus-salience capture hypothesis*; e.g., Theeuwes, 1992, 1994). Others have argued that involuntary capture by objects occurs only when they match to what you are looking (known as the *contingent capture hypothesis*; e.g., Folk, Remington, & Johnston, 1992). This controversy in the field of attention capture provided the motivation for undertaking the current study, with the

hope that new methodology might provide additional insight into the issue. Before delving into the precise functioning of our methods, we should first have a deeper look at the field of involuntary attention capture.

Involuntary Attention Capture by Stimulus Salience vs. Contingent Capture

Attentional capture was first thought to be driven by stimulus properties, with evidence from abrupt onset studies that utilized immediate presentation of a previously absent stimulus as either a distractor or target. Yantis and Jonides (1984) presented a target by removing line segments from figure-8 (as would be found in a digital clock) images to form letters (P, E, S, H and U). Shortly after the letters were revealed (80 ms), an additional letter would abruptly appear at a different location on the screen. Participants were told to look for a specific letter and to respond to its presence or absence with a keypress. Yantis and Jonides found that response time (RT) increased significantly with display size when the target was not the abrupt onset, whereas RT was relatively stable in conditions that the target was an abrupt onset. This suggests that the abrupt appearance of even an irrelevant item triggers a shift of visual attention to process the new information.

This has been further expanded by evidence from later studies to include other salient stimulus properties, such as singletons, that capture attention regardless of task relevance. At the forefront of this research has been Theeuwes (1991, 1992, 1994), who simultaneously presented an irrelevant singleton with the target display. Participants responded to the orientation of a line that was embedded in either a color or shape

singleton amongst a circular display of items, and in the key manipulation, a secondary singleton was presented simultaneously at one of the distractor locations for half of the trials. This singleton was irrelevant, in that it would be a shape singleton when the participants were told to look for color and a color singleton when the target defining feature was shape. He found that the presence of an irrelevant singleton prolonged RT to the target in both color and shape conditions. This increase in RT is explained by participants allocating attention to the distracter before returning to the target item, leading Theeuwes to argue that salient singletons will initially capture attention, regardless of search instructions (i.e., the top-down task set).

The capture by stimulus salience view was challenged by Folk et al. (1992). They argued that salient stimuli capture attention only when they share relevant features with the target. In the case of previous studies illustrating capture by salient stimuli, the results are explained by participants engaging in search for a unique object (e.g., an onset target). In supporting their argument, they adopted a cuing paradigm where an uninformative cue was presented prior to the target. By combining two types of cues (onset vs. singleton) with both onset and color target conditions, they were able to compare the effects of relevant and irrelevant cues on RT. The onset cue was the abrupt appearance of white dots around one of the boxes that designated each display location, while the color cue contained red dots at one box and white dots around the other boxes. The cue appeared at one of the four display locations but only validly indicated the following target in 25% of the trials, giving participants no incentive to attend to it. The target display was similar in that the onset target was the only

appearing letter and the color target was defined as the red letter with white letters appearing in the other display locations.

As an index of the capture by the cue, they measured the cue validity effect – an attended cue that validly indicates the target location will produce faster RT than an attended cue that invalidly indicates the target location. This works on the rather intuitive principle that if attention is already allocated to the target location shortly before it appears (in the case of a valid cue), it will take less time to identify the target than if attention is allocated elsewhere (in the case of neutral or invalid cues). By comparing the differences between the valid and invalid trials for both the relevant and irrelevant cues (known as the cue validity effect), Folk et al. (1992) found that attention was captured by the color cue in the color target condition but not in the onset target condition. Likewise, the onset cue failed to capture attention in the color target condition, but produced a significant cue validity effect for the onset condition. They concluded that salient objects do not have inherent power to capture attention involuntarily unless they contain the feature that relates to the person's goal. Numerous studies have subsequently supported this conclusion (e.g., Bacon & Egeth, 1994; Folk & Remington, 1998; Lien, Ruthruff, Goodin, & Remington, 2008; Remington, Folk, & McLean, 2001).

Search Strategies: Singleton Detection vs. Feature Search

Bacon and Egeth (1994) explained the results of Theeuwes (1992) and Folk et al. (1992) by suggesting that capture by objects is highly dependent on search strategies. They propose two distinct strategies which they call *singleton detection* mode and

feature search mode. In *singleton detection* mode, the observer relies on the difference between elements and their background to direct attention (i.e., searching is driving by the unique object in the display). This strategy is analogous to Theeuwes' stimulus salience model and serves as a default strategy for visual search. *Feature search* mode is a strategy that is dependent on top-down influence and is based on observer expectations of the target's identifying features (i.e., searching is driving by the specific feature that defines the target). In *feature search* mode, observers will presumably monitor a feature map and direct attention to elements that cause activation of the feature map. While only *singleton detection* is useful when the target-defining feature is unknown, it is possible to use either search strategy when the target is known. In these cases, the demands of the task dictate which strategy will be utilized.

In Theeuwes attention capture paradigm, for instance, the participants may not have been looking for the target defining feature of shape, but rather using *singleton detection* since the target was always a singleton. That is to say participants will scan for any unique items in a display if they know that the target is going to be an unique item, which makes it unsurprising that any singleton would capture attention, regardless of its relevance to the target. In the Folk et al. cueing paradigm, however, the participants may have used *feature search* to ignore the irrelevant cues. Their adoption of this strategy is demonstrated by the fact that only precues of the relevant dimension produced a cue-validity effect, despite their status as singletons. Bacon and Egeth (1994) supported this view by using a display similar to Theeuwes but included multiple targets that shared the relevant identity, or increased the diversity of the non-target

items, making singleton search ineffective. With the target selection requiring a specific feature, they found that salient-but-irrelevant singletons failed to produce interference and they concluded that irrelevant but salient singletons did not capture attention under these conditions. Even though participants could use feature search in Theeuwes paradigm, it is likely that singleton detection is easier and more efficient for the given task, dissuading the use of feature search.

Theeuwes (2004) disagrees with this explanation, claiming that these types of search strategies do not exist. According to Theeuwes, the results found in Bacon and Egeth (1994) can be explained as the result of increased noise in the display. This is to say that the supposedly salient singletons were simply not salient enough given the background; they did not 'pop-out' in the display. This would cause the participants to utilize serial search, which attenuates the effect of salient distracters (Gibson & Peterson, 2001). In order to increase salience of the target and distractor, Theeuwes (2004) increased the number of non-target items in the display. The results showed an insignificant search slope between 12 and 20 display items, compared to the small but statistically significant difference found between display sizes of 5 and 9 items in both Theeuwes and Bacon and Egeth (1994). Theeuwes (2004) argues that what actually was occurring was serial processing, and not the engagement of a specific search strategy, and thus there was not a top-down influence on the initial allocation of attentional resources.

Leber and Egeth (2006) leveled several charges against Theeuwes (2004) study, while acknowledging the criticisms of Bacon and Egeth's (1994) design. First of all, they

accepted the serial search criticism, but raised the caveat, that since there was no indication of where the target would be, the distracter should reside in the participant's attentional window prior to starting serial search, and therefore should cause some interference. In addition, Leber and Egeth (2006) acknowledged that increasing the display size in fact increased the salience of the singleton items, but suggested that it encouraged the use of a salience based search strategy. Since Theeuwes used fewer unique items in his display, and increased background homogeneity, participants could quickly search within the small set of singletons, a strategy that was unavailable to participants in Bacon and Egeth. In order to avoid the issues raised by serial search slopes, Leber and Egeth used a two-part experiment that included a training and a test phase. In the training phase, participants were presented with heterogeneous displays and instructed to respond to either unique objects (the singleton condition) or a specific feature (the feature condition). The participants were then tested using displays similar to Theeuwes (1992), which is historically considered to be a parallel search paradigm. The results indicated a clear divide between those in the singleton condition and those in the feature condition; the color distracter captured attention only in participants that had been trained to search for unique objects.

Challenges to the Contingent Capture View

As further evidence against the contingent capture view, Theeuwes, Atchely, and Kramer (2000) argued that the results of Folk et al. (1992) study could be explained by what has been termed the disengagement hypothesis. The disengagement hypothesis suggests that attention is captured by the irrelevant cue but is rapidly disengaged prior

to the target display. This would have to happen extraordinarily quickly, which was supported by Theeuwes et al. who found that it could occur within 150 ms by varying the stimulus onset asynchrony (SOA) between the onsets of the distractor and the target. The study used a similar design as prior attention capture studies, with a circular item display in which the participant would search for shape singleton. The key manipulation was the presence of a color singleton that could appear 50, 100, 150, 200, 250, or 300 ms prior to the signaling of the target. While the absence of a distracter produces the fastest RT, the effect of having a distracter was greatest at 100 ms, the effect largely disappeared by 150 ms and there were no gains in RT with additional increases in SOA.

In response to this was the idea of filtering cost as proposed by Remington et al. (2001), which suggested that the increased number of salient objects would require additional processing at the preattentive level. The issue at hand highlights the concern with using RT as the main evidence for a theory involving the some of the minutest preliminary processes of human cognition. Using behavioral methods such as RT leaves a lot of room for alternative explanations, which is why a direct measure of attention capture is necessary to clarify the discrepancies in the behavioral data.

Event-Related Potentials Studies of involuntary Attention Capture

Of particular usage are electrophysiological measures such as brain wave components measured in event-related potentials (ERP). The present study examined the N2pc (N2 posterior-contralateral) effect of ERPs. This N2pc component is an increased negativity found over the posterior scalp contralateral to an attended

stimulus. To clarify this, the N2pc effect to a target in the left visual field would be measured by quantifying the difference between the voltages measured at electrode sites on right (contralateral) and left (ipsilateral) hemifields, with greater voltage differences suggesting a greater degree of attentional allocation to the left side (see Figure 1). This effect is thought to reflect localized attentional filtering as opposed to eye movements or stimulus differences (Luck & Hillyard, 1994), making it a sensitive and specific measure of the allocation of attention. In addition, the N2pc effect has the advantage of providing information on both the temporal and spatial aspects of these shifts of attention (see Eimer, 1996; Eimer & Kiss, 2008; Woodman & Luck, 2003).

With this technology there have been several recent studies that have supported both sides of the debate. Hickey, McDonald, and Theeuwes (2006) used a similar display as Theeuwes (2000) and found an N2pc effect elicited by the irrelevant singleton when it was presented laterally with the target on the vertical meridian. Since the target was along the vertical axis, any N2pc effect would be due to attention being allocated to one of the sides. Perhaps more telling is a small N2pc effect to an irrelevant singleton prior to an effect to the target when the distractor and the target are presented on opposite sides. While this would be strong evidence for the hypothesis that salient stimuli capture attention initially, there is still the possibility that participants were involved in singleton search strategy.

A recent study by Lien, Ruthruff, and Cornett (2010) suggests that this may be the case. Following Folk et al.'s (1992) cueing paradigm, Lien et al. increased the number of colors in the target display and manipulated the saliency of the cue display. The use

of a cueing paradigm has the benefit of isolating the ERP components elicited to the cue and to the target, which eliminates the potential confounds of a simultaneously presented distractor and target (as in the case of Hickey et al.'s, 2006, study). To encourage the use of a top-down search strategy for the target color, the target display was always a non-singleton display, containing at a color target and at least one color distractor. Thus, the use of a singleton search for the target provided no benefit. There were three cuing conditions, a relevant cue condition in which an uninformative color singleton of the target color was present with items of a homogenous nontarget color, an irrelevant cue condition in which a non-target color singleton was present among items of a homogenous nontarget color and the more interesting competing cue condition in which a non-target color singleton was present amidst a homogenous background of target color items. While the relevant and irrelevant cue conditions produced similar results to prior studies, the competing cue condition provided powerful evidence against the salience capture hypothesis by showing no capture effects by the non-target color singleton cue. Furthermore, the color cue did not produce a significant effect when shape was the target defining feature. In simpler terms, the color singleton only produced the N2pc effect when it shared the target color. It appears that a color singleton by itself is not enough to guarantee capture of spatial attention.

The Present Study

Though Lien et al. (2010) found that the saliency of a singleton may not be sufficient to capture attention voluntarily, it is possible that a singleton can capture

attention if the display enhances the pop-out effect (i.e., increasing the salience of the singleton). The goal of this study is to attempt to create conditions in which a strong top-down setting for a target is needed in a singleton (or pop-out) display; to pit a feature search strategy against a cueing display that strongly promotes salience capture. To accomplish this need, we used a go/no-go cueing paradigm. Participants determined whether the target-colored letter was present (go trials) or absent (no-go trials). They made a two-choice response (e.g., the red letter was a "T" or "L") for the go trials but withheld their response for the nogo trial (e.g., when the target red letter was absent). To perform this task efficiently, participants should adopt a top-down control setting for the target color, as to avoid errors caused by attending to possibly irrelevant singletons.

Our main question of interest is whether the irrelevant, salient color singleton in the cue display could capture attention even when it did not match the defined target. The cue validity was manipulated (25% valid vs. 75% invalid). Thus, there was little incentive to direct attention to the cue location. Behavioral measures (cue validity effects on RT and proportion of errors) and ERP measures (N2pc effect to the color singleton cue) were used. Though behavioral measures require the participants to make a response, ERPs can be found even when no response is required (i.e., no-go trials). If singletons have the power to capture attention through the pop-out effect of high saliency, then we should see N2pc effects to the color singleton regardless of whether it contains the defined target feature. However if singletons capture attention only when they match to the top-down control setting as suggested by the contingent

capture view, then we should obtain N2pc effect to the singleton that contains the target feature.

EXPERIMENT 1

Experiment 1 was a control experiment to verify our color singleton target display had the power to capture spatial attention, as measured using an N2pc effect. To induce a top-down control setting for color, each participant was instructed to respond only to one of the colored targets (red or green; a between-subject variable) when it was present (go trials) and to withhold response when it was absent (no-go trials). Thus, in order to perform the task optimally, participants had to establish the proper task set (i.e., the specific color). All participants received the same displays with the only difference being the instructions regarding the target color. Although there was no singleton cue in this experiment, we presented a neutral cue display with all boxes being white to make the event sequence and time course similar to that of the subsequent experiments (see Figure 2A). There were 50% go trials and 50% no-go trials.

Methods

Participants. Fourteen undergraduate students (4 male) from Oregon State University participated in exchange for extra course credit. Their mean age was 20 years (range: 18-22). Half of the participants were assigned to the red target condition and the other half to the green target condition. All reported having normal or corrected-to-normal acuity and normal color vision. All participants demonstrated normal color vision using the Ishihara Test for color deficiency.

Apparatus and Stimuli. Stimuli, displayed on 19-inch ViewSonic monitors, were viewed from a distance of about 55 cm. Within each trial, three stimulus events were presented in succession (see Figure 2A): the fixation display, the cue display, and target display. Although the cue display was identical to the fixation display in this experiment, it was included to provide a similar event sequence as those in subsequent experiments (see Figures 2A-2B).

The fixation display consisted of five boxes: a center box surrounded by four peripheral boxes (top-left, bottom-left, top-right, and bottom-right). Each peripheral box was equidistant from the center box (7.81º, center to center) and from adjacent peripheral boxes (10.81º, center to center). Each box was 2.60º × 2.60º, drawn with thin (0.10º) white lines. The neutral cue display was identical to the fixation display. The target display consisted of the fixation display plus a letter (1.04º width × 1.35º length × 0.31º thick in Arial font) inside each of the four peripheral boxes. Each hemifield (left vs. right) contained one "T" and one "L". One letter was either red (RGB values: 255, 0, 0) or green (RGB values of 102, 204, 51), and the other letters were white (RGB values of 255, 255, 255). Thus, the target display was a color singleton display.

Design and Procedure. As shown in Figure 2A, each trial started with the presentation of the fixation display for 1,200 ms. Then, as a warning signal, the center box was turned off for 100 ms. The fixation display then reappeared for 1,200 or 1,400 ms, determined randomly. This was followed by a neutral cue display, which in this experiment was identical to the fixation display, for 50 ms. The fixation display reappeared again for 100 ms and was followed by the target display which appeared for

50 ms before returning to the fixation display. The participants' task was to indicate whether the letter in the target color was a T or L (go trials), or to withhold response if the target color was absent (no-go trials). Specifically, participants were to press the leftmost response-box button with their left-index finger for the target letter "L" and the rightmost button with their right-index finger for the target letter "T".

The target was present for 50% of trials and was absent for the remaining 50% of trials. The next trial began with the 1,200-ms fixation display immediately following a response or after 3 seconds in the target-present trials or after 1.5 seconds in the target-absent trials. Participants performed one practice block of 32 trials, followed by 16 experimental blocks of 64 trials each (a total of 1,056 experimental trials). The target locations were randomly determined with the equal probability of occurring in each location. For the go trials, a tone was presented for 100 ms if participants made an incorrect response or did not respond within 3 seconds. For the no-go trial, participants received a warning message (i.e., "No target letter. Please do not respond") on the screen for 800 ms if they made a response. After each block, participants received a summary of their mean RT and accuracy, and were encouraged to take a break.

EEG Recording and Analyses. The electroencephalographic (EEG) activity was recorded from F3, F4, C3, C4, T7, T8, P3, P4, P5, P6, PO5, PO6, O1, and O2. These sites and the right mastoid were recorded in relation to a reference electrode at the left mastoid. The ERP waveforms were then re-referenced offline to the average of the left and right mastoids. The horizontal electrooculogram (HEOG) was recorded bipolarly from electrodes at the outer canthi of both eyes, and the vertical electrooculogram

(VEOG) was recorded from electrodes above and below the midpoint of the left eye. Electrode impedance was kept below 5 kΩ. EEG, HEOG, and VEOG were amplified using Synamps2 (Neuroscan) with a gain of 2,000 and a bandpass of 0.1-50 Hz. The amplified signals were digitized at 500 Hz.

Trials with artifacts were identified in two steps. First, trials with artifacts were rejected automatically using a threshold of ± 75μV for a 1,000 ms epoch beginning 200 ms before neutral cue onset to 1,200 ms after neutral cue onset. Each of these candidate artifact trials was then inspected manually. To determine whether individual participants systematically moved their eyes in response to the stimulus, we computed for each participant average HEOG waveforms when the stimulus appeared to the left and right visual fields, separately, during the period 200-300 ms after the target display onset. Following Woodman and Luck (2003), we included in the data analyses only participants whose average HEOG activity was less than ±3μV during this time window. For the ease of comparison with the subsequent experiments where the cue elicited N2pc effect was measured, the ERP waveforms were time-locked to the onset of the cue display. To quantify the overall magnitude of the N2pc effect, we focused on the time window identified in previous studies as showing the largest effects: 200-300 ms after target display onset (350-450 ms after the cue onset; see e.g., Lien et al., 2008). Specifically, the N2pc effect was measured as mean amplitude during this time window for contralateral electrode sites to the stimulus location minus for ipsilateral electrode sites to the stimulus location at the P5/P6, O1/O2, and PO5/PO6 electrode sites, relative

to the mean amplitude during a 200 ms pre-cue onset baseline period. Same procedure was applied for both go and no-go trials.

Results

In addition to excluding trials with EEG artifacts, we excluded trials from the final analyses of behavioral data (RT and proportion of error [PE]) and ERP data if RT was less than 100 ms or greater than 1,500 ms (This accounted for < 0.07% of trials). Rejection of trials with EEG artifacts led to the further elimination of 5.95% of trials, with no more than 18.05% rejected for any individual participants. An analysis of variance (ANOVA) was performed, with the *p* values being adjusted using the Greenhouse-Geisser epsilon correction for non-sphericity, where appropriate. An alpha level of .05 was used to determine statistical significance. The data analyses were conducted averaged across the group (red vs. green target) variable, in which showed no effect on behavioral and EEG data.

Behavioral Data Analyses. Experiment 1 was designed to establish the time course for the N2pc effect. There were no factors of interest relevant to the behavioral data in this experiment. Thus, we reported only the mean data for the go trials. The mean RT was 550 ms and the mean PE was 0.02. The false alarm rate was less than 0.001.

ERP Data Analyses. The difference waveform data (i.e., N2pc effects) were analyzed as a function of trial type (Go vs. No-Go) and electrode pair (P5/P6, O1/O2, and PO5/PO6). We analyzed the average value of the difference waveform at 350-450 ms after the neutral cue onset to assess the target-elicited N2pc effect. Each subcondition

contained a total of 512 trials before rejecting trials that were incorrect, fell outside our RT cutoff, or showed ocular artifacts.

Target-Elicited N2pc Effects. Our primary aim was to determine whether our display captured attention and produced N2pc effects. The N2pc effect was found to be larger for go than no-go trials, $F(1,13)=10.30$, $p < 0.01$; the effect was -1.353 μV for go trials and was -0.461 μV for no-go trials. The further t-test analyses revealed that the N2pc effects for both go and no-go trials were significant, $t(13)=-4.30$, $p < 0.001$, and $t(13)=-3.89$, $p < 0.01$, respectively. No other effects were significant.

Discussion

As expected the paradigm illustrated capture of spatial attention for the relevant go target singleton, as shown by a large N2pc effect that did occur during 200-300 ms after target onset (350 to 450 ms after the neutral cue onset). One notable finding is that although the size of the N2pc effect elicited by the non-target color letter in the no-go trials was only about 1/3 of effect elicited by the target letter in the go trials (see Figure 3), it was still statistically significant. These findings suggest two implications. First, the non-target color stimuli (on the no-go trials) still captured attention and produced an N2pc effect in the time course similar to the effect in the go trials. A possible explanation for this is that when the display contained a color singleton, participants searched the colored item first (i.e., a singleton detection search) before deciding whether it contained the target color (go) or not (no-go). Second, the smaller N2pc effect for the no-go trials than the go trials implies that the N2pc effect reflects attentional selectivity (e.g., Eimer, 1996), rather than attentional suppression of

competing information from nearby distractors with the potential to interfere with target identification (e.g., Luck & Hillyard, 1990, 1994; Woodman & Luck, 1999). Note that there was only one colored object in the target display in Experiment 1. Thus, the N2pc effect elicited by the target cannot be attributed to the suppression of the distractors in the display. We will provide further discussion on these two issues in General Discussion.

Experiment 2

In Experiment 2, we implemented our main manipulation by adding a color singleton cue before the target display, to determine whether a color singleton has the power to capture spatial attention, regardless of top-down control settings. Capture of spatial attention would be identified with a cue validity effect and an N2pc effect. The singleton cue and the target locations were randomly determined with the equal probability of occurring in each location. Thus, the location of the singleton cue could be the same as the location of the target for 25% of the trials (the valid condition). The remaining trials (75%) were invalid, giving the participants no incentive to attend to the singleton cue in the cue display.

Although our experimental logic relies primarily on electrophysiological (i.e., the N2pc effect), we can also look for converging evidence in the behavioral data. Specifically, capture to the singleton cue location should result in a cue validity effect: faster RT and/or lower PE when the singleton cue was in the same location (valid trials) as the upcoming target than when it was not (invalid trials).

In the ERP data, capture to the color singleton cue location should produce an N2pc effect. Thus, in addition to the time window where the target would produce an N2pc effect (350-450 ms after cue onset) as in Experiment 1, we analyzed the ERP data on the time window where the color singleton would likely to produce an N2pc effect (150-250 ms after cue onset) (see Lien et al., 2008). To make the ERP analyses and figures consistent with each other, we analyzed both the cue-elicited N2pc effect and the target-elicited N2pc effect with respect to the singleton cue location rather than the target location. Thus, when the singleton cue and the target stimulus are in the same hemifield, they should produce an N2pc effect in the same direction. When they are in different hemifields, however, the polarity of the N2pc effect to the target stimulus should be opposite to that of the singleton cue.

Methods

Participants. Twenty new undergraduate students (8 male), drawn from the same participant pool as in Experiment 1, participated in this experiment. Their mean age was 20 years (range: 18-23). All reported having normal or corrected-to-normal acuity and normal color vision. As in Experiment 1, half of the participants were instructed to respond to the red letters and the other half to the green letters. All participants demonstrated normal color vision using the Ishihara color test.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except for the cue display. One of the box frames changed color from white to the target-related color or the non-target color (i.e., the color singleton cue; see Figure 2B for an example). This design generated two types of cue

validity conditions. In the valid condition (25% of trials), the location of the color singleton cue was the same as the location of the target. In the invalid condition (75% of trials), the location of the color singleton cue was different from the location of the target. Same cue validity manipulation was used for the colored, non-target letter for the no-go trials. As in Experiment 1, the proportion of go and no-go trials was 50% and 50%.

Results

The data analysis was similar to that of Experiment 1. The false alarm rate (making a response when there was no target) was 1.4%. Application of the RT cutoffs eliminated approximately 0.10% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 6.7% of trials, but no more than 19.65% for any individual participant.

Behavioral Data Analyses.

The behavioral data, including only go trials, were analyzed as a function of singleton cue type (relevant vs. irrelevant) and validity (valid vs. invalid). As in Experiment 1, the group (red vs. green) did not show a main effect or interactions with any variable. Therefore, we excluded it from the final analyses to simplify the analyses. Tables 1 and 2 show mean RT and PE, respectively, for each condition.

The mean RT was 13 ms shorter for the relevant color singleton cue (M = 559 ms) than for the irrelevant color singleton cue (M = 572 ms), $F(1, 19) = 10.31$, $p < .01$, $\eta^2_p = 0.35$. The cue validity effect on RT was 27 ms, $F(1, 19) = 61.96$, $p < .0001$, $\eta^2_p = 0.77$; mean RT was 552 ms for valid trials and was 579 ms for invalid trials. The interaction

between these two variables was also significant, $F(1, 19) = 43.21$, $p < .0001$, $\eta^2_p = 0.69$; the cue validity effect was 49 ms for the relevant singleton cue but was only 5 ms for the irrelevant singleton cue. The further t-test analyses revealed that the cue validity effect was significant for the relevant singleton cue, $t(19) = 13.58$, $p < .0001$, but not for the irrelevant singleton cue, $t(19) < 1.0$.

As in RT data, the cue validity effect on PE was significant, $F(1, 19) = 18.00$, $p < .001$, $\eta^2_p = .49$; the cue validity effect was .008. No other effects were found to be significant.

ERP Analyses. The N2pc data were analyzed as a function of trial type (go vs. no-go), electrode site (P5/P6, O1/O2, vs. PO5/PO6), singleton cue type (relevant vs. irrelevant), and singleton cue/target spatial relationship (same hemifield vs. different hemifields). Figure 4 shows the N2pc effects averaged across the three electrode pairs for the go and no-go trials. Each condition contained a total of 128 trials before trials that fell outside our RT cutoff or showed ocular artifacts were rejected. We analyzed the average N2pc effect over two different time windows: 150-250 ms after singleton cue onset (to assess the N2pc effect elicited by the singleton cue) and 350-450 ms after singleton cue onset (to assess the N2pc effects elicited by the target).

Cue-Elicited N2pc Effects. Our primary goal was to determine whether singleton cue captures attention and produce N2pc effects. Results for the time window 150-250 ms after singleton-cue onset showed that the N2pc effect was significant larger for the relevant cue (-1.666 μV) than for the irrelevant cue (-1.177 μV), $F(1, 19) = 7.38$, $p < .05$, $\eta^2_p = .28$. Neither the main effect of trial type nor its interaction with the cue type were

significant, *F*s < 1.0. The overall N2pc effect was -1.436 μV for go trials and -1.407 μV for no-go trials. For the go trials, the N2pc effect elicited by the relevant cue (-1.718 μV) was significantly larger than the irrelevant cue (-1.155 μV), $F(1, 19) = 6.29$, $p < .05$, $\eta^2_p = .25$. Similarly, for the no-go trials, the N2pc effect was larger for the relevant cue (-1.615 μV) than for the irrelevant cue (-1.199 μV), $F(1, 19) = 6.60$, $p < .05$, $\eta^2_p = .26$. The further two-tailed t-tests on the N2pc effect elicited by the irrelevant cue showed that the effect was still significant for go trials, $t(19) = -6.75$, $p < .0001$, and for no-go trials, $t(19) = -5.95$, $p < .0001$.

The P5/P6 and PO5/PO6 electrode pairs produced larger N2pc effect than the O1/O2 electrode pair, $F(2, 38) = 11.12$, $p < .001$, $\eta^2_p = .37$; the effects were -1.532 μV and -1.662 μV for the P5/P6 and PO5/PO6 electrode pairs, respectively, but was only -1.071 μV for the O1/O2 electrode pair. This difference was larger for the relevant cue than the irrelevant cue, $F(2, 38) = 6.12$, $p < .01$, $\eta^2_p = .24$. For the relevant cue, the N2pc effects were -1.821 μV, -1.956 μV, and -1.222 μV, for the P5/P6, PO5/PO6, and O1/O2 electrode pairs, respectively. For the irrelevant cue, the N2pc effects were -1.243 μV, -0.919 μV, and -1.368 μV, for the P5/P6, PO5/PO6, and O1/O2 electrode pairs, respectively. No other effects were found to be significant.

Target-Elicited N2pc Effects. We also conducted the target-elicited N2pc effect analyses although these data do not allow a test of our main hypothesis. Also note above, because we defined the N2pc effect with respect to the singleton cue location (for consistency with the N2pc figures), the direction of the target-elicited N2pc effect should depend critically on whether the singleton cue and target appeared in the same

or different hemifield. That is, the target-elicited N2pc effects would be negative in polarity (i.e., a normal N2pc effect) when the target appeared in the same hemifield as the cue but positive (i.e., a reversed N2pc effect) when it appeared in the opposite hemifield as the cue.

As in Experiment 1, the target-elicited N2pc effect was significantly larger for the go trials (0.335 μV) than for the no-go trials (0.016 μV), $F(1, 19) = 8.18$, $p < .01$, $\eta^2_p = .30$. The target-elicited N2pc effect was more positive with the relevant cue (0.346 μV) than with the irrelevant cue (0.004 μV), $F(1, 19) = 7.60$, $p < .05$, $\eta^2_p = .29$. This pattern was observed regardless of whether it was a go or no-go trial, $F < 1.0$. A normal target-elicited N2pc effect was observed for the same hemifield condition (-0.709 μV), but the effect was reversed for the different hemifield condition (1.060 μV), $F(1, 19) = 71.28$, $p < .0001$, $\eta^2_p = .79$. The pattern was more pronounced for the go trials (-1.106 μV for the same hemifield and 1.776 μV for the different hemifield conditions) than for the no-go trials (-0.321 μV for the same hemifield and 0.343 μV for the different hemifields conditions), $F(1, 19) = 55.95$, $p < .0001$, $\eta^2_p = .75$.

The overall target-elicited N2pc effect was more positive for the P5/P6 (0.353 μV) and PO5/PO6 (0.144 μV) electrode pairs than for the O1/O2 electrode pair (0.029 μV), $F(2, 38) = 7.17$, $p < .01$, $\eta^2_p = .27$. This pattern was observed when the singleton cue and target were in different hemifields but not when they were in the same hemifield, $F(2, 38) = 5.04$, $p < .05$, $\eta^2_p = .21$. In the different hemifield condition, the N2pc effects were 1.252 μV, 1.140 μV, and 0.787 μV for the P5/P6, PO5/PO6, and O1/O2 pairs, respectively. In the same hemifield condition, the N2pc effects were -

0.547 μV, -0.852 μV, and -0.728 μV for the P5/P6, PO5/PO6, and O1/O2 pairs, respectively. The 3-way interaction between trial type, singleton cue/target spatial relationship, and electrode site was significant, $F(2, 38) = 19.06$, $p < .0001$, $\eta^2_p = .50$, so was the 4-way interaction between these variables and singleton cue type, $F(2, 38) = 3.25$, $p < .05$, $\eta^2_p = .15$. No other effects were found to be significant.

Discussion

Experiment 2 examined attentional allocation to a salient color singleton cue in the presence of a top down setting. The go vs. no-go paradigm was designed to promote a top down search setting for the target feature, in this case color. The behavioral data confirmed previous findings showing that a cue validity effect was obtained only when the cue contained the color used to find the target (an overall 49 ± 7 ms validity effect at the 95% confidence interval; e.g., Folk et al., 1992; Lien et al., 2008; Lien et al., 2010). This finding suggests that the relevant cue captured attention to its location, facilitating the target processing when it appeared in that location but hampering the target processing when it appeared in some other location. However, the irrelevant cue (e.g., the green box in the cue display when the target was a red letter) produced relatively small, non-significant cue validity effect (4 ± 12 ms at the 95% confidence interval). This finding by itself supports the contingent capture hypothesis, suggesting that involuntary attention capture depends on top-down attentional control settings even in a singleton display.

Interestingly, the ERP data (e.g., N2pc effects) suggest that a more complicated processing might have occurred than that indicated by the behavioral data (e.g., RT).

The relevant cue produced a substantial N2pc effect (-1.666 μV) during the interval 150-250 ms following the singleton cue onset. This finding is consistent with the behavioral data (i.e., the cue validity effect on RT), indicating capture by the objects sharing the feature that is critical for finding the target. However, the irrelevant cue produced a N2pc effect that was significant and substantial (-1.177 μV), $t(19) = -6.59$, $p < .0001$, albeit smaller than the relevant cue, similar to the N2pc effect found in Experiment 2. The reduction in the N2pc effect was only 28%. Furthermore, the N2pc effects elicited by the relevant cue and by the irrelevant cue did not differ between go and no-go trials (see Figure 4). These results, inconsistent with the contingent capture hypothesis, indicate that color singletons capture attention, even if they don't resemble the target color. In fact, the N2pc effect elicited by the irrelevant cue was just as large as that to the target, suggesting that attentional system does not make any distinction between them.

While behavioral data (i.e., cue validity effects) suggest contingent capture, the ERP data suggest capture by saliency regardless of the top-down control setting. The conflict between these two data highlights the importance of using multiple measures, but also demands an explanation. It is possible that the irrelevant color singleton cues captured attention only briefly (producing an N2pc effect), releasing attention before the target arrived (producing little cue validity effect). That is to say that attention was initially deployed, but returned to a 'ready state' by the time the target display appeared. This explanation is plausible and would also explain the reversal of the N2pc effect during 250-350 ms after the cue onset for both relevant and irrelevant cues (see

Figure 4). Similar reversal of the N2pc effect was also obtained in several of previous studies (e.g., Lien et al., 2008; Luck & Hillyard, 1994). This effect can simply be due to that attention was captured by the color singleton cues initially but was returned to the neutral position prior the target onset. However, this explanation would need a further assumption to accommodate the observed small albeit non-significant cue validity effect for the irrelevant cue. That is, the returning to the neutral position is not always completed prior to the target onset (see Lien et al., 2008, for further discussion). However, this explanation fails to take into account the absence of the target-elicited N2pc effect for the no-go trials (see Figure 4, the bottom panel), which suggests no evidence for capture by the non-target color letter. Overall, the finding implies that the top-down control setting can override the capture by salience.

Experiment 3

The goal of Experiment 3 was to discourage the use of singleton search, and thereby increase the incentive to utilize top-down control (an attentional set for only the target color). This was accomplished by increasing the number of different non-target colors from 1 to 3 (e.g., green, blue, and yellow for the target color red). The logic behind this is that participants may have used singleton search initially and then determined the nature of the singleton object (e.g., red for go and green for no-go when red was the target color) in the target display. Increasing the number of potential colors for the target display would reinforce the top-down task set of target feature (e.g., red for go). Participants were also specifically instructed to search for a specific target color (e.g., red) without giving them the specific non-target colors. The design was similar to

Experiment 2 – color singleton cue and target displays were used. Only one colored object appeared in the cue and the target displays (i.e., a singleton display). The proportion of go and no-go trials was still 50% and 50%.

If attention capture by salient color singletons occurs regardless of the top-down control setting, then one would expect that the irrelevant color singleton cues would capture attention. That is, similar cue validity effect and the N2pc effect should be obtained for both relevant and irrelevant cues. On the other hand, if contingent capture can override the stimulus salience even in the singleton display, then the capture effects should only be evident for the relevant cues but not for the irrelevant cues.

Method

Participants. There were 20 new participants (5 male), drawn from the same participant pool as in the previous experiments. Their mean age was 21 years (range: 18-28). One fourth of the participants responded to the red letters, one fourth responded to the green letters, one fourth to the blue letter, and the remaining one fourth responded to the yellow letters. All reported having normal or corrected-to-normal acuity and demonstrated normal color vision using the Ishihara color test.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 2, except that four different colors were used in both cue and target displays. In addition to the red and green used in previous experiments, blue (RGB values: 0, 51, 255) and yellow (RGB values: 255, 255, 0) were used. One of these four colors served as the target color (go trials) and the remaining three served as the non-target colors (no-go trials) for each participant. Participants were given an

instruction for the target color but not the non-target colors. The assignment of colors to the target and non-target colors was counterbalanced between participants.

Results

The data analysis was similar to that of Experiment 2. The overall false alarm rate was 4.4%. Application of the RT cutoffs eliminated approximately 0.07% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 3% of trials, but no more than 10% for any individual participant.

Behavioral Data Analyses. As in Experiment 2, the behavioral data analyses included only go trials. The group (red, green, blue, vs. yellow target) did not show a main effect or interactions with any variable. Therefore, we excluded it from the final analyses. As in Experiment 2, the ANOVA on both RT and PE were conducted as a function of singleton cue type (relevant vs. irrelevant) and validity (valid vs. invalid). Tables 1 and 2 show the mean RT and PE, respectively, for each condition.

The mean RT was 10 ms shorter for the relevant cue (M = 569 ms) than the irrelevant cue (M = 579 ms), $F(1, 19) = 8.63$, $p < .01$, $\eta^2_p = 0.31$. The overall cue validity effect on RT was 21 ms, $F(1, 19) = 34.30$, $p < .0001$, $\eta^2_p = 0.64$; mean RT was 563 ms for valid trials and was 584 ms for invalid trials. The interaction between these two variables was also significant, $F(1, 19) = 24.43$, $p < .0001$, $\eta^2_p = 0.56$; the cue validity effect was 36 ms for the relevant singleton cue but was only 6 ms for the irrelevant singleton cue. The further t-test analysis showed that the cue validity effect for the irrelevant singleton cue approached to be significant, $t(19) = 1.91$, $p = .0713$.

As in RT data, the cue validity effect on PE was significant, $F(1, 19) = 7.57$, $p < .05$, $\eta^2_p = .06$; the cue validity effect was .012. No other effects were found to be significant.

ERP Analyses. The N2pc data were analyzed as a function of trial type (go vs. no-go), electrode site (P5/P6, O1/O2, vs. PO5/PO6), singleton cue type (relevant vs. irrelevant), and singleton cue/target spatial relationship (same hemifield vs. different hemifields). As in Experiment 2, the N2pc effect data analyses focused on two time windows: 150-250 ms after singleton cue onset to assess the N2pc effect elicited by the singleton cue and 350-450 ms after singleton cue onset to assess the N2pc effects elicited by the target. Figure 5 shows the N2pc effects averaged collapsed across the three electrode pairs for the go and no-go trials.

Cue-Elicited N2pc Effects. As in Experiment 2, the cue-elicited N2pc effect analyses showed that the N2pc effect was significant larger for the relevant cue (-1.213 μV) than for the irrelevant cue (-0.883 μV), $F(1, 19) = 5.73$, $p < .05$, $\eta^2_p = .23$. The overall N2pc effect was similar for go trials (-1.034 μV) and no-go trials (-1.062 μV), $F < 1.0$. The interaction of trial type and the cue type were not significant either, $F < 1.0$. For the go trials, the N2pc effect elicited by the relevant cue (-1.178 μV) was significantly larger than the irrelevant cue (-0.890 μV), $F(1, 19) = 4.69$, $p < .05$, $\eta^2_p = .20$. For the no-go trials, the N2pc effect was numerically larger for the relevant cue (-1.247 μV) than for the irrelevant cue (-0.877 μV), although it approached to be significant, $F(1, 19) = 3.27$, $p = .0864$, $\eta^2_p = .15$. The further two-tailed t-tests on the N2pc effect elicited by the irrelevant cue showed that the effect was still significant for go trials, $t(19) = -3.87$, $p < .001$, and for no-go trials, $t(19) = -3.95$, $p < .001$.

The singleton cue produced a larger N2pc effect when the cue and the target were in the same hemifields than when they were in different hemifields for go trials (-1.120 μV and -0.947 μV, respectively), but a smaller N2pc effect for the no-go trials (-0.910 μV and -1.215 μV, respectively), $F(1, 19) = 9.58$, $p < .01$, $\eta^2_p = .34$. Similarly, the relevant singleton cue produced a larger N2pc effect when it and the target were in the same hemifields than when they were in different hemifields for go trials (-1.275 μV and -1.151 μV, respectively), whereas the irrelevant singleton cue produced smaller N2pc effect for the same hemifield condition (-0.755 μV) than the different hemifields condition (-1.012 μV), $F(1, 19) = 5.69$, $p < .05$, $\eta^2_p = .23$. No other effects were found to be significant.

Target-Elicited N2pc Effects. For the target-elicited N2pc effect analyses (350-450 ms after the cue onset), a normal N2pc effect was observed when the target appeared in the same hemifield as the singleton cue (-0.041 μV) but the effect was reversed when it appeared in the opposite hemifield (1.209 μV), $F(1, 19) = 18.96$, $p < .001$, $\eta^2_p = .50$. In addition, the P5/P6 and PO5/PO6 electrode pairs produced more positive N2pc effects (0.816 μV and 0.644 μV, respectively) than the O1/O2 electrode pair (0.233 μV), $F(2, 38) = 15.89$, $p < .0001$, $\eta^2_p = .46$. The interaction between trial type and singleton cue/target spatial relationship was significant, $F(1, 19) = 59.51$, $p < .0001$, $\eta^2_p = .76$. For the go trials, the target produced a normal N2pc effect (-0.562 μV) when it appeared in the same hemifields as the singleton cue but the effect was reversed when it appeared in the opposite hemifield (1.867 μV). For the no-go trials, however, the target produced reserved N2pc effects for both same hemifield condition (0.480 μV)

and different hemifield condition (0.551 μV). No other effects were found to be significant.

Discussion

Experiment 3 increased the incentive to establish a top-down attentional set for only the target color by increasing the number of non-target colors from 1 to 3. As in Experiment 2, we used a singleton cue display and a singleton target display. Replicating Experiment 2, a substantial cue validity effect was obtained for the relevant cue (36 ± 12 ms at the 95% confidence interval), where the singleton cue contained the color used to find the target. This effect, although smaller, is similar to the cue validity effect of 49 ms obtained in Experiment 2, $t(38) = 1.86$, $p = .0705$. In addition, the cue validity effect was again small, non-significant for the irrelevant cue (6 ± 7 ms at the 95% confidence interval), where the singleton cue contained the non-target color. This small effect was not significantly different from the 4 ms obtained in Experiment 2, $t(38) = -1.72$, $p = .0943$. Thus, the behavioral data again provide no evidence that irrelevant color singleton captured attention when the target itself was also a singleton.

Nevertheless, as in Experiment 2, the N2pc data suggest otherwise. As expected, the relevant cue again produced substantial N2pc effects regardless of whether it was a go trial or no-go trial. Although the irrelevant cue produced a smaller N2pc effect than the relevant cue (27% smaller), the effect was still substantial and significant for both go and no-go trials. The reduction in the N2pc effect for the irrelevant cue was similar to that in Experiment 2 (29%). Therefore, results of Experiment 3 suggest that even with the increased incentive to utilize top-down control setting by increasing the number of

non-target colors from 1 to 3, the irrelevant singleton cue still captured attention. The dissociation between the behavioral data and the ERP data was observed not only in Experiment 3 but also in Experiment 2, implying that the dissociation is genuine.

Experiment 4

Despite the strong incentive for top-down control setting in Experiment 3, the salient but irrelevant color singletons still captured attention. Experiment 4 took one step further for strong stop-down control setting by using a non-singleton target display – two colored letters along with two white letters in every target display (see Figure 2C for an example). Under this condition, relying on a singleton search strategy would prove ineffective at identifying the target, and thus should incentivize the use of a feature-detection strategy for the target color. This procedure was used successfully for showing no capture by the irrelevant color singleton cue in previous studies (e.g., Lien et al., 2010). As in previous experiments, a go/no-go paradigm was used, although the target display was changed to contain one target-colored letter and one non-target colored letter on go trials and two non-target-colored letters on no-go trials. These two colored letters were always in the opposite hemifields to allow for the hemifield sensitive N2pc effect to differentiate between attention allocated to either colored letter.

Method

Participants. There were 20 new participants (10 male), drawn from the same participant pool as in the previous experiments. Their mean age was 21 years (range: 18-28). One fourth of the participants responded to the red letters, one fourth to the

green letters, one fourth to the blue letter, and the remaining fourth responded to the yellow letters. All reported having normal or corrected-to-normal acuity and demonstrated normal color vision using the Ishihara color test.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 3, except the target display. Instead of presenting one colored letter with three white letters (a singleton display), we presented two colored letters with two white letters (a non-singleton display). The two colored letters were always on the opposite hemifields (Figure 2C). One of the two colored letters was in the target color for 50% of the trials (go trials) and both colored letters were in the non-target color for the remaining 50% of the trials (no-go trials). Again, participants were given an instruction for the target color but not the non-target colors.

Results

The data analysis was similar to that of Experiment 3. The false alarm rate was 8%. Application of the RT cutoffs eliminated approximately 0.45% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 6% of trials, but no more than 25% for any individual participant.

Behavioral Data Analyses. As in Experiment 3, the ANOVA on both RT and PE of go trials were conducted as a function of singleton cue type (relevant vs. irrelevant) and validity (valid vs. invalid). Tables 1 and 2 show the mean RT and PE, respectively, for each condition.

As in Experiment 3, the mean RT was 14 ms shorter for the relevant cue (M = 600 ms) than the irrelevant cue (M = 614 ms), $F(1, 19) = 14.51$, $p < .01$, $\eta^2_p = 0.43$. The

overall cue validity effect on RT was 30 ms, $F(1, 19) = 39.09$, $p < .0001$, $\eta^2_p = 0.67$; mean RT was 592 ms for valid trials and was 622 ms for invalid trials. The cue validity effect was 52 ms for the relevant singleton cue but was only 8 ms for the irrelevant singleton cue, $F(1, 19) = 41.27$, $p < .0001$, $\eta^2_p = 0.68$. The further t-test analysis showed that the cue validity effect for the irrelevant singleton cue approached to be significant, $t(19) = 1.86$, $p = .0784$.

For PE data, the cue validity effect approached to be significant, $F(1, 19) = 3.69$, $p = .0698$, $\eta^2_p = .16$; the cue validity effect was .003. No other effects were found to be significant.

ERP Analyses. Because there was one target and one non-target in the target display for go trials but two non-targets in the no-go trials (one on each hemifield), trial type and singleton cue/target spatial relationship are not orthogonal. They cannot be included in the same ANOVA. Therefore, we conducted two different ANOVAs for each N2pc analysis below. The first ANOVA including all trials were analyzed as a function of trial type (go vs. no-go), electrode site (P5/P6, O1/O2, vs. PO5/PO6), and singleton cue type (relevant vs. irrelevant). The second ANOVA including only go trials were analyzed as a function of electrode site (P5/P6, O1/O2, vs. PO5/PO6), singleton cue type (relevant vs. irrelevant), and singleton cue/target spatial relationship (same hemifield vs. different hemifields). In the latter analyses, we reported only the significant effects involved the singleton cue/target spatial relationship (same hemifield vs. different hemifields).

As in previous experiments, the N2pc effect data analyses again focused on two time windows: 150-250 ms after singleton cue onset to assess the N2pc effect elicited

by the singleton cue and 350-450 ms after singleton cue onset to assess the N2pc effects elicited by the target. Figure 6 shows the N2pc effects averaged collapsed across the three electrode pairs for the go and no-go trials.

Cue-Elicited N2pc Effects. The first ANOVA including both go and no-go trials revealed that the cue-elicited N2pc effect was larger for the relevant cue (-0.941 μV) than the irrelevant cue (-0.643 μV), $F(1, 19) = 7.84$, $p < .05$, $\eta^2_p = .29$. As in Experiment 3, the overall N2pc effect was similar for go trials (-0.736 μV) and no-go trials (-0.849 μV), $F(1, 19) = 2.29$, $p = .1464$, $\eta^2_p = .11$. The interaction of trial type and the cue type were not significant either, $F < 1.0$. For the go trials, the N2pc effect elicited by the relevant cue (-0.742 μV) was similar to that elicited by the irrelevant cue (-0.609 μV), $F(1, 19) = 1.48$, $p = .2385$, $\eta^2_p = .07$. For the no-go trials, the N2pc effect was significantly larger for the relevant cue (-1.014 μV) than the irrelevant cue (-0.634 μV), $F(1, 19) = 7.15$, $p < .05$, $\eta^2_p = .27$. The further two-tailed t-tests on the N2pc effect elicited by the irrelevant cue showed that the effect was still significant for go trials, $t(19) = -4.08$, $p < .001$, and for no-go trials, $t(19) = -5.07$, $p < .0001$.

The interaction between cue type and electrode sites was significant, $F(2, 38) = 3.97$, $p < .05$, $\eta^2_p = .17$. The N2pc effect elicited by the relevant cue was larger for the PO5/PO6 electrode pair (-1.091 μV) than the P5/P6 and O1/O2 electrode pairs (-0.953 μV and -0.779 μV, respectively). The N2pc effect elicited by the irrelevant cue was larger for the P5/P6 electrode pair (-0.704 μV) than the PO5/PO6 and O1/O2 electrode pairs (-0.686μV and -0.583 μV, respectively). No other effects were found to be significant.

The second ANOVA including the variable of singleton cue/target spatial relationship (same hemifield vs. different hemifields) was conducted only for go trials. The N2pc effect was larger when the singleton cue and target were in the same hemifield (-1.010 μV) than when they were in different hemifields (-0.668 μV) for the relevant cue but was smaller for the irrelevant cue (-0.554μV and -0.711 μV, respectively), $F(1, 19) = 3.86$, $p = .0642$, $\eta^2_p = .17$. No other effects were found to be significant.

Target-Elicited N2pc Effects. For the target-elicited N2pc effect analyses (350-450 ms after the cue onset), the first ANOVA including both go and no-go trials showed that the reversal of N2pc effect was larger for the relevant cue (0.595 μV) than for the irrelevant cue (0.288 μV), $F(1, 19) = 4.92$, $p < .05$, $\eta^2_p = .21$. The target-elicited N2pc effect was also larger for the P5/P6 and PO5/PO6 electrode pairs (0.683 μV and 0.427 μV, respectively) than for the O1/O2 electrode pair (0.255 μV), $F(2, 38) = 16.53$, $p < .0001$, $\eta^2_p = .55$. No other effects were found to be significant.

The second ANOVA including the variable of singleton cue/target spatial relationship (same hemifield vs. different hemifields) was conducted only for go trials. The data analyses showed that a normal N2pc effect was observed when the target appeared in the same hemifield as the singleton cue (-0.499 μV) but the effect was reversed when it appeared in the opposite hemifield (1.463 μV), $F(1, 19) = 45.63$, $p < .0001$, $\eta^2_p = .71$. This pattern was similar for both relevant and irrelevant cues, $F < 1.0$ (see Figure 6).

Discussion

Experiment 4 further increased the incentive to look for a specific target color by placing two colored letters in every target display (alone with two white letters; i.e., a non-singleton target display). Thus, the use of the singleton detection mode to perform the task was impossible. As in previous experiments, the proportion of the go and no-go trials was 50/50. The overall RT was longer in Experiment 4 (604 ms) than that in Experiment 3 (574 ms), suggesting that the non-singleton target display promotes the use of a top-down control set which slowed down the target response. The use of the non-singleton target design also allowed us to test the singleton detection mode hypothesis, in which irrelevant color singletons should capture attention only when the target itself was also a singleton. As in previous experiments, the cue display remained a color singleton and should only have captured attention when it matched the target feature.

Replicating Experiments 2 and 3, the relevant cue produced a substantial cue validity effect on RT (52 ± 15 ms at the 95% confidence interval). The irrelevant cue again produced small cue validity effect (8 ± 9 ms at the 95% confidence interval) that was not significantly different from that in Experiment 3 (6 ± 7 ms), $t(38) = -0.38$, $p = .7094$. As expected, the behavioral data provide evidence that when the target was not a singleton, color singletons captured attention only when they match to the defining target feature. However, this merely replicates the findings found in Experiments 2-3, which suggests that the target display did not change the way attention was allocated to the cue display.

The electrophysiological evidence supports this position. As in Experiments 2-3, the irrelevant cue produced significant N2pc effects for both go and no-go trials (-0.609 μV and -0.634 μV, respectively). The effect was only 28% in average smaller than the effect elicited by the relevant cue. This small effect was similar to those in Experiments 2-3 (29% vs. 27%, respectively). Therefore, results of Experiment 4 suggest that even with the increased incentive to utilize top-down control setting by using a non-singleton target display, the irrelevant singleton cue still captured attention. Additionally, the target display continued to produce an N2pc effect only in the go condition.

Experiment 5

Experiment 5 took a further step to increase incentive for utilizing top-down control setting (i.e., a feature search mode) by increasing the colored letters in the target display from 2 to 4. That is, each one of the 4 letters contained a unique color (e.g., red, green, blue, yellow, or white). Figure 2D shows an example of the target display. As in previous experiments, the target color appeared for 50% of the trials (go trials) and was absent for the other 50% of the trials (no-go trials). Therefore, the use of a singleton detection mode to detect the target letter was absolutely ineffective. Again, if attention capture by irrelevant singleton is solely driven by stimulus saliency, then we should obtain evidence of capture (the N2pc effect and the cue validity effect) for the irrelevant cue. That capture effect should be similar in degree as the effect obtained by the relevant cue. In contrary, if the involuntary attention capture is driven by the top-down control setting, then we should see capture only by the relevant cue that contains the target color.

Method

Participants. There were 20 new participants (9 male), drawn from the same participant pool as in the previous experiments. Their mean age was 20 years (range: 18-29). As in Experiment 4, one fourth of the participants responded to the red letters, one fourth to the green letters, one fourth to the blue letter, and the remaining fourth responded to the yellow letters. All reported having normal or corrected-to-normal acuity and demonstrated normal color vision using the Ishihara color test.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 4, except the target display. Each of the 4 letters in the target display contained a unique color – red, green, blue, yellow, or white, with one of the first 4 colors serving as a target color for each participant (see Figure 2D). The location of the colors was randomly determined. As in Experiment 4, the target color was present for 50% of the trials (go trials) and was absent for the remaining 50% of the trials (no-go trials). Again, participants were given an instruction for the target color but not the non-target colors.

Results

The data analysis was similar to that of Experiment 4. The false alarm rate was 6%. Application of the RT cutoffs eliminated approximately 1.25% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 4% of trials, but no more than 15% for any individual participant.

Behavioral Data Analyses. As in Experiment 4, the ANOVA on both RT and PE of go trials were conducted as a function of singleton cue type (relevant vs. irrelevant) and

validity (valid vs. invalid). Tables 1 and 2 show the mean RT and PE, respectively, for each condition.

As in Experiment 4, the overall cue validity effect on RT was 27 ms, $F(1, 19) = 27.34$, $p < .0001$, $\eta^2_p = 0.59$; mean RT was 577 ms for valid trials and was 604 ms for invalid trials. The cue validity effect was 49 ms for the relevant singleton cue but was only 6 ms for the irrelevant singleton cue, $F(1, 19) = 35.12$, $p < .0001$, $\eta^2_p = 0.65$. The further t-test analysis showed that the cue validity effect for the irrelevant singleton cue was not significant, $t(19) = 1.18$, $p = .2537$.

For PE data, the overall cue validity effect was .019, $F(1, 19) = 13.07$, $p < .01$, $\eta^2_p = .41$; mean PE was .022 for valid trials and was .041 for invalid trials. No other effects were found to be significant.

ERP Analyses. As in Experiment 4, we conducted two different ANOVAs for each N2pc analysis below. The first ANOVA including all trials were analyzed as a function of trial type (go vs. no-go), electrode site (P5/P6, O1/O2, vs. PO5/PO6), and singleton cue type (relevant vs. irrelevant). The second ANOVA including only go trials were analyzed as a function of electrode site (P5/P6, O1/O2, vs. PO5/PO6), singleton cue type (relevant vs. irrelevant), and singleton cue/target spatial relationship (same hemifield vs. different hemifields). In the latter analyses, we reported only the significant effects involved the singleton cue/target spatial relationship (same hemifield vs. different hemifields).

As in Experiment 4, the N2pc effect data analyses again focused on two time windows: 150-250 ms after singleton cue onset to assess the N2pc effect elicited by the singleton cue and 350-450 ms after singleton cue onset to assess the N2pc effects

elicited by the target. Figure 7 shows the N2pc effects averaged collapsed across the three electrode pairs for the go and no-go trials.

Cue-Elicited N2pc Effects. The first ANOVA including both go and no-go trials revealed that the cue-elicited N2pc effect was larger for the relevant cue (-1.623 μV) than the irrelevant cue (-1.106 μV), $F(1, 19) = 18.14$, $p < .001$, $\eta^2_p = .49$. The overall N2pc effect was larger for go trials (-1.455 μV) than no-go trials (-1.274 μV), $F(1, 19) = 4.89$, $p < .05$, $\eta^2_p = .20$. The interaction of trial type and the cue type approached to be significant, $F(1, 19) = 3.50$, $p = .0767$, $\eta^2_p = .16$. For the go trials, the N2pc effect elicited by the relevant cue (-1.774 μV) was significantly larger than the effect elicited by the irrelevant cue (-1.136 μV), $F(1, 19) = 19.74$, $p < .001$, $\eta^2_p = .51$. Similarly, for the no-go trials, the N2pc effect was significantly larger for the relevant cue (-1.472 μV) than the irrelevant cue (-1.076 μV), $F(1, 19) = 9.10$, $p < .01$, $\eta^2_p = .32$. The further two-tailed t-tests on the N2pc effect elicited by the irrelevant cue showed that the effect was still significant for go trials, $t(19) = -6.51$, $p < .0001$, and for no-go trials, $t(19) = -5.70$, $p < .0001$.

The main effect of electrode site was significant, $F(2, 38) = 8.23$, $p < .01$, $\eta^2_p = .30$; the N2pc effect elicited by the singleton cue was smaller for the O1/O2 electrode pair (-1.050 μV) than the P5/P6 and PO5/PO6 electrode pairs (-1.533 μV and -1.511 μV, respectively). The interaction between cue type and electrode sites was significant, $F(2, 38) = 7.69$, $p < .01$, $\eta^2_p = .29$. The N2pc effect elicited by the relevant cue was largest for the P5/P6 electrode pair (-1.869 μV) than the P5/P6 and O1/O2 electrode pairs (-1.757 μV and -1.244 μV, respectively). The N2pc effect elicited by the irrelevant cue was

largest for the PO5/PO6 electrode pair (-1.265 μV) than the P5/P6 and O1/O2 electrode pairs (-1.197 μV and -0.856 μV, respectively). The interaction between trial type and electrode sites was significant, $F(2, 38) = 4.94$, $p < .05$, $\eta^2_p = .21$. The N2pc effect for the go trials was largest for the P5/P6 electrode pair (-1.704 μV) than the P5/P6 and O1/O2 electrode pairs (-1.573 μV and -1.087 μV, respectively). The N2pc effect for the no-go trials was largest for the PO5/PO6 electrode pair (-1.449 μV) than the P5/P6 and O1/O2 electrode pairs (-1.361μV and -1.012 μV, respectively). No other effects were found to be significant.

The second ANOVA including the variable of singleton cue/target spatial relationship (same hemifield vs. different hemifields) was conducted only for go trials and revealed no effects involved this variable to be significant.

Target-Elicited N2pc Effects. For the target-elicited N2pc effect analyses (350-450 ms after the cue onset), the first ANOVA including both go and no-go trials showed that the reversed N2pc effect was larger for the P5/P6 and PO5/PO6 electrode pairs (0.404 μV and 0.157 μV, respectively) than for the O1/O2 electrode pair (0.003 μV), $F(2, 38) = 5.76$, $p < .01$, $\eta^2_p = .23$. The interaction between electrode pairs and cue type was also significant, $F(2, 38) = 3.90$, $p < .05$, $\eta^2_p = .17$. For the relevant singleton cue, the reversed N2pc effect was much larger for the P5/P6 (0.531 μV) than the PO5/PO6 and O1/O2 electrode pairs (0.292 μV and 0.027 μV, respectively). For the irrelevant singleton cue, the difference in N2pc effects was smaller between these electrode pairs (0.277 μV, -0.020 μV, and 0.021 μV for the P5/P6, O1/O2, and PO5/PO6, respectively). No other effects were found to be significant.

The second ANOVA including the variable of singleton cue/target spatial relationship (same hemifield vs. different hemifields) was conducted only for go trials. The data analyses showed that a normal N2pc effect was observed when the target appeared in the same hemifield as the singleton cue (-1.003 μV) but the effect was reversed when it appeared in the opposite hemifield (1.312 μV), $F(1, 19) = 37.60$, $p < .0001$, $\eta^2_p = .66$. This difference was larger for the relevant cue (-1.072 μV and 1.583 μV for the same and different hemifields, respectively) than for the irrelevant cue (-0.935 μV and 1.042 μV for the same and different hemifields, respectively), $F(1, 19) = 14.34$, $p < .01$, $\eta^2_p = .43$ (see Figure 7). The interaction between electrode pairs and singleton cue/target spatial relationship was also significant, $F(2, 38) = 12.60$, $p < .0001$, $\eta^2_p = .39$. When the target appeared in the same hemifield as the singleton cue, the normal N2pc effect was larger for the PO5/PO6 (-1.088 μV) than the O1/O2 and P5/P6 electrode pairs (-0.893 μV and -1.030 μV, respectively). When the target appeared in the opposite hemifield to the singleton cue, the reversed N2pc effect was larger for the P5/P6 (1.626 μV) than the O1/O2 and PO5/PO6 electrode pairs (0.887 μV and 1.424 μV, respectively).

Discussion

Experiment 5 further increased the incentive to look for a specific target color by placing four colored letters in every target display. As in previous experiments, the proportion of the go and no-go trials was 50/50. The overall RT was 590 ms, similar to the RT of 604 ms in Experiment 4, suggesting that the non-singleton target display with two or four unique colors led similar top-down control processing. If serial search was being performed, we would expect there to be a greater difference . Replicating

Experiment 4, the relevant cue produced a substantial cue validity effect (49 ± 16 ms at the 95% confidence interval). However, the irrelevant cue again produced small, non-significant cue validity effect (6 ± 10 ms at the 95% confidence interval). This effect was not significantly different from that in Experiment 4 (6 ± 7 ms), $t(38) = 0.43$, $p = .6695$. Thus, the behavioral data provide evidence that, when the target was not a singleton, color singleton cues captured attention only when they match to the defining target feature.

As in Experiment 4, the N2pc data suggest otherwise. The irrelevant cue produced significant N2pc effects for both go and no-go trials (-1.136 μV and -1.076 μV, respectively). The effect was 32% in average smaller than the effect elicited by the relevant cue (-1.774 μV and -1.472 μV for go and no-go trials, respectively). This small effect was similar to those in Experiments 2-4 (29%, 27%, and 28% respectively). Consistent with previous experiments, therefore, results of Experiment 5 suggest that even with the increased incentive to utilize top-down control setting by using a non-singleton target display, the irrelevant singleton cue still captured attention.

GENERAL DISCUSSION

Purpose

The goal of the present study was to determine if salience alone is sufficient to capture attention, pitting a strong top-down control setting against a highly salient but sometimes irrelevant object. To address this we used a modified cuing paradigm with a go/no-go task in which participants were asked to make one of the two responses for go trials but withheld responses for no-go trials. The key manipulation was the relevance of

the singleton cue display to the target. In addition to behavioral measures, we utilized the N2pc as a measure of attentional capture, as it provided both an online measure of attention capture but also could record attention on no-go trials in which there was no behavioral response. Prior research has provided conflicting evidence supporting both the salience capture hypothesis (Theeuwes, 1992) as well as for the contingent capture hypothesis (Folk et al., 1992). One explanation of the results of the experiments that support contingent capture is that the target displays did not have a 'pop-out' effect, meaning that the background of the target displays was too homogenous to be searched using parallel search. The use of a go/no-go task allowed us to utilize a singleton display, while still encouraging a strong top-down control setting (Verbruggen & Logan, 2008). In this task, the participants were asked to make one of the responses for go trials but withheld responses for no-go trials. A cue-validity effect was predicted by the contingent capture hypothesis for the target relevant cues, while the salience capture hypothesis predicted a cue-validity effect for both relevant and irrelevant cues, given their equal salience. Likewise, the contingent capture hypothesis also predicted an N2pc effect to the relevant cue while the salience capture hypothesis predicted that an N2pc effect would be similar in both relevant and irrelevant conditions.

Summary of results

The results of our research were remarkably consistent between experiments, indicating the robustness of our findings. In Experiment 1, we illustrated the ability of our singleton display to produce the N2pc ERP component, indicating attentional capture to the target. The non-target color singleton also produced an N2pc effect

though it was of significantly lesser magnitude than to the target color. With the introduction of the singleton cue display prior to the target display in Experiment 2, we observed a significant cuing effect on RT and PE, but only for the relevant color cue. Consistent with the behavioral data, the ERP data also revealed a large N2pc effect for the target color cue. The irrelevant cue elicited a small but significant N2pc effect. These results persisted in Experiments 3-5, in which we continually increased the strength of the top-down setting by increasing the complexity of the target display. Thus we find behavioral results that are generally consistent with contingent capture, while our electrophysiological results show an N2pc to both relevant and irrelevant singleton cues, albeit of significantly smaller magnitude to the irrelevant cues.

The present study made several hypotheses about our results. If the original contingent capture hypothesis was correct, we expected that only the relevant target color singleton cues would capture attention, producing both a behavioral cue validity effect as well as an N2pc to the relevant cue, but no cue validity effect or N2pc to the irrelevant cue. In many ways, our results supported this hypothesis, showing a significant cue validity effect and a strong N2pc in the relevant cue condition. In addition, the irrelevant cue condition failed to produce a significant cue validity effect. These findings suggest that top-down control settings do modulate attentional capture, but do not prove that top-down settings are able to completely override the salience of the singleton display.

However, our electrophysiological results also provided strong evidence against the contingent capture hypothesis with the significant, albeit smaller, N2pc to the

irrelevant target in Experiment 1 and the irrelevant cue display in the subsequent experiments. The salience capture theory also made several hypotheses regarding the outcome of our experiment. Given that the cue displays (Experiments 2 through 5) contained a highly salient pop-out singleton, the salience capture hypothesis would predict capture by the cue regardless of the relevance. That is, similar cue validity effects and N2pc effects should be observed in both the relevant and irrelevant conditions. The lack of a cue validity effect in the irrelevant condition provides evidence against the salience capture hypothesis, but given that this experiment partially replicates prior cuing paradigms (e.g., Eimer, Kiss, Press, & Sauter, 2009; Folk et al., 1992; Folk & Remington, 1998; Lien et al., 2008) that have been inconclusive to salience capture supporters, these results alone are insufficient to disprove the theory. While the interpretation of behavioral findings in cuing paradigms are subject to ongoing debate, the electrophysiological results lend support to the salience capture hypothesis, with significant N2pc effects found to the irrelevant singleton cue. However, the results found were not those predicted by the current theory of salience capture, given that the N2pc effect was significantly smaller in the irrelevant condition than in the relevant condition. Given that the cue displays were identical in each color condition, with only the instructions varying, they should have had identical salience and therefore produced N2pc effects of the same magnitude, regardless of relevance to the task.

These results are also not explained by Bacon and Egeth's (1994) search strategy hypothesis of contingent capture. If the participants were utilizing a singleton search strategy there should have been a cue validity effect for both the relevant and irrelevant

cue, as well as a similar N2pc to both. This suggests that our paradigm was successful in preventing participants from using this strategy. Yet, there is also evidence that the participants were not using feature detection mode either. Feature detection mode does predict our findings that there would only be a cue validity effect only in the case of the relevant cue condition, but also that only the relevant cue would produce a significant N2pc. Another possibility is that a mix of search strategies was adopted across trials for each participant or across participants. Thus, the attenuated N2pc represents the averaging of trials in which the N2pc was present due to singleton search and when it was absent due to feature detection. This also might be found if some of the participants used singleton detection, while others used feature search mode. However, our go/no-go paradigm was designed to discourage the use of singleton detection mode, and from Experiments 4 onward, the non-singleton target display would have provided further disincentive for the strategy. The difficulty in explaining our results with the search strategy hypothesis can be interpreted as evidence against the theory.

Our findings raise serious questions about the current theories of attentional capture. The consistent appearance of the N2pc effect elicited by the irrelevant cue suggests that attention is driven by bottom up factors, yet it is clear that the N2pc is modulated by task instructions, indicating a top down influence in how attention is allocated. These results of our research suggest that neither the contingent capture hypothesis nor the salience capture hypothesis is adequate to explain exogenous attention capture. Instead, our findings provide evidence for an interaction between

top-down and bottom-up influences which will need to be accounted for in future theories.

Alternative Theories

Given the apparently inconsistent findings for both contingent capture and salient capture views, it is important that we investigate the possible explanations. First, a primary reason for using electrophysiological evidence, such as the N2pc component, is that they provide greater sensitivity than behavioral measures, especially to the time course of events. Since there was a 150 ms delay between the onset of the cue display and the target display, it is possible that attention may have been allocated to and then rapidly disengaged from an irrelevant cue prior to the target onset (Theeuwes**,** Atchley, & Kramer, 2000). If attention was able to disengage and return to a neutral position, as is suggested by the disengagement hypothesis, then it is possible that our behavioral measures simply lacked the sensitivity to demonstrate attentional capture by irrelevant singletons. Because of these concerns we designed our experiment to rely primarily on the electrophysiological measures that are more sensitive to the temporal aspects of the attention capture.

However, as stated above, the electrophysiological results are equally enigmatic. The N2pc elicited by both the relevant and irrelevant cues is consistent with the salience capture hypothesis, yet the persistent differences between these N2pc suggest that top-down control somehow modulates the capture of attention as suggested by the contingent capture hypothesis. Thus our results do not provide conclusive evidence for neither the salience capture nor the contingent capture hypothesis. In fact our results

are not explained by either. In order to explain our results both theories must be expanded, and the N2pc effect may need to be reinterpreted in light of these data.

N2pc as multiple components

It is possible that our results could be explained if the N2pc reflects multiple components. One component is the result of an initial stage of attentional capture that is spatially localized and dependent on object salience that occurs. This initial capture followed by a slow, top-down process, which modulates the degree of capture. Some previous studies have suggested that N2pc effects are driven by target selection (Hickey et al., 2006; Mazza, Turatto, & Caramazza 2009; Woodman & Luck, 2003), whereas others suggest that they are driven by distractor suppression (Luck, 2005; Luck & Hillyard, 1994). It is impossible in the current paradigm to determine whether this modulation effect represents enhancement of target features or suppression of non-target features. Regardless, the difference found between the magnitude of the irrelevant and the relevant condition N2pcs would be accounted for by this modulation effect. Since the irrelevant condition does not contain the target feature, the singleton cue either receives no enhancement or is actively inhibited. In either case, our findings suggest the co-existence of both effects in the relevant and irrelevant conditions. In other words, salience alone is enough to drive attentional capture and that it is only after attention has been captured that top-down control settings influence further processing and resource allocation.

This is supported by Hickey, Di Lollo, and McDonald's (2009) study which suggests that the N2pc to the target is modulated by feedback connections from higher-

level cortical areas to lower-level sensory areas. Using an additional singleton paradigm as in Theeuwes (1991) with lateralized target and distractor conditions, Hickey et al. (2009) found that slow RT was associated with earlier peaks in the distractor elicited N2pc, while fast RT corresponded to early peaks in the target elicited N2pc, with distractor elicited N2pc occurring earlier than the N2pc to the target for both slow and fast RT (though not significantly in the fast RT). These results are explained as the lag between the initial salience driven processes in the lower-level sensory areas and the top-down reentrant feedback from cortical areas. While this research supports that the N2pc can be modulated by stimulus relevance, there was no significant main effect of eliciting stimulus on amplitude such as we found in the current study.

Other research suggests the possibility that the modulation effect is a result of a pre-stimulus top-down control setting that weights incoming stimulus according to task goals. Sawaki and Luck (2010) explored the Pd (distractor positivity) component and N2pc component to test the hypothesis that salient singletons always generate an attention capture signal, but this signal can be actively suppressed to avoid capture. Though the Pd component has only recently been characterized, it is thought to represent attentional suppression. Sawaki and Luck found that Pd component occurred prior to the N2pc, and proposed that stimuli generate an 'attend-to-me' signal, which in the absence of a top-down control setting will cause a shift of attention to the location of a salient stimulus. However, if there is a strong top-down control setting, presumably mediated by the prefrontal cortex and dependent on the availability of working memory resources, the attend-to-me signal will be suppressed and attention will not be shifted.

They call this the *signal suppression hypothesis of controlled attention capture*. It is important to note that the Pd component does not directly reflect the attend-to-me signal, but instead is a measure of active distractor suppression. The Pd component is also unlikely to reflect attentional capture, given that it was found independent of an N2pc component. This hypothesis does not directly explain the results found in our study, given that we were not looking for the Pd component. However, a deeper look at the Pd does suggest that it is the modulation effect we are looking for. Unfortunately, the balanced design of our study prevented us from separating the Pd component from the N2pc as a whole.

The Pd was first characterized by Hickey et al. (2008) not as an additional component to the N2pc, but as one of its constituent parts. They used a sparse search display design in which the two stimulus items (either a colored square or a line) could appear at one of four lateralized positions or two along the vertical meridian. By comparing the condition with a lateralized target and a distractor along the vertical meridian to the condition with a lateralized distractor and a target on the vertical meridian, they were able to identify two distinct components. When the target was at a lateralized location and the distractor was along the vertical meridian, an ERP negativity – characterized as the Nt component – was found contralateral to the target. When the target and distractor positions were reversed, an ERP positivity – the Pd component – was found contralateral to the distractor. Crucial to these findings, the target identifying features was varied between participants, suggesting that this effect was not related to target features but rather task goals. Additionally the Pd component was found at a

latency of 220-260 ms, the same latency as the Nt component. If the N2pc reflects the summation of these two components, our findings are easily explained. The salience of both the relevant and irrelevant singleton cues in our display drives the Nt component, but since the irrelevant singleton does not match the task goals, it receives suppression expressed as the Pd component. The summation of Nt and Pd component results in a smaller N2pc effect to the irrelevant cue than found to the relevant cue, which receives less lateralized suppression.

The multiple component hypothesis of the N2pc seems to provide the best explanation for our findings, as well as the results of previous studies. While bottom-up processes appear to be responsible for driving attentional selection based largely on stimulus salience, these processes do not operate independently. Top-down modulation of attention capture does occur, and can occur preattentively, as suggested by the findings of Sawaki and Luck (2010). However, unlike the bottom up processes, top-down influence depends on the mediation of higher cortical areas. The very nature of top-down modulation means that it is likely to be highly variable and both the amplitude of the Pd component and its latency are going to depend on a large number of factors in the individual as well as the experimental design. Further research will be needed to determine which factors play dominant roles in the top-down modulation of attention capture.

Practical Limitations

The results of our study highlight some of the key methodological and theoretical issues in the field of attentional capture research. First is the disparity

between the behavioral and electrophysiological results, which provided for conflicting conclusions regarding the irrelevant cue condition. The cuing effect, which has been widely used in the literature as a measure of attentional allocation should be revisited, with particular attention being paid to experimental designs that have a longer SOA between the cue and the target display. In the current study the SOA was only 150 ms, meaning that attention can both be partially deployed and successfully disengaged within this timeframe.

With the limitations of behavioral measures, the use of electrophysiology seems like a godsend. EEGs have a high temporal resolution and can peer into the brain, allowing us to measure activity prior to a behavioral response or without a behavioral response entirely. Despite these benefits, electrophysiology suffers from a series of drawbacks. These drawbacks largely stems from the fact that ERPs are correlates, despite often being referred to as direct or online measures. As Luck (2005) explicates, "the functional significance of an ERP component is virtually never as clear as the functional significance of a behavioral response" (p. 22). This is to say the brain activity we measure is not the same as the process that we relate it to. The N2pc effect is not attention capture, but it appears regularly when we would expect attention to be captured, and may represent a number of related or unrelated processes, as suggested by the multiple component hypothesis. Additionally, this lack of clarity extends to variation in the ERP components. While the multiple component hypothesis of the N2pc may explain some of the variation in amplitude, there remains much to discover regarding what effects the amplitude and time course of the N2pc.

Theoretical Limitations

While there is ongoing debate over the nature of the N2pc and/or its components, a more theoretical concern must be addressed. Attention research requires a definition of attention as a foundation, a foundation which is shakier than most researchers would care to admit. Despite William James's 1890 assertion that *"Everyone knows what attention is"* the word carries increasingly complex connotations that categorize it with terms like divided, selective, overt, covert, sustained, focused and executive attention. Additionally it is increasingly connected with other mental processes and constructs like working memory, vigilance and executive function. The term has come to describe a multitude of related but different phenomena. Attention can be considered a resource or capacity to maintain concentration, as a state of consciousness characterized by concentration, as well as concentration itself. Most researchers do not clarify which of these they are studying, relying on the assumption that others can decipher their definitions from the methodology and claims they make.

The problem of that is of most significance to the field of attention capture is the uncertainty regarding what 'attentional capture' actually is. While most researchers are content with the definition that it is the cognitive process of selectively concentrating on a particular aspect of the environment, there is considerably less consensus as to what constitutes that process. Often this leads to the paradigm operationally defining attention capture in the particular way that it is being measured, rather than the process it represents. Take for example the dichotomy between Folk et al. (1992) and Theeuwes (1992). In Folk et al. (1992), attention capture is measured as the presence of

a cue validity effect, while Theeuwes (1992) defines it as the RT and accuracy cost of an additional salient stimuli. In each case, something is being measured and significant differences are present, but a string of inferences is required to link these differences to attentional capture**.** Now the N2pc is also established as an operational definition for attentional capture (Eimer, 1996; Eimer & Kiss, 2008; Hickey et al., 2006; Lien et al., 2010; Luck, 2005; Luck & Hillyard, 1994; Mazza et al., 2009; Woodman & Luck, 2003) largely because it has been a good tool for measuring attentional capture. But given that we are continually exploring new measures, like the Pd component, the definition of the N2pc will change and therefore this definition of attentional capture will have to be rewritten as well. Our findings also reveal an additional issue with using ERP measures, in that the amplitude and time course of ERPs may reflect meaningful differences in processing, suggesting that capture exists along a continuum rather than as discrete states.

The use of different operational definitions is largely what prevents the field of attention capture from reaching a consensus in the top-down vs. bottom-up debate. Simply put, without a universally accepted definition that clearly and completely defines the boundary between what is captured and what is not, we cannot reach a conclusion as to what drives attentional capture. It may even be the case that the debate is not meaningful, in that is possible to create a definition of attentional capture the entirely precludes top-down influence, or that makes it an integral and necessary component. Until the definition is agreed upon, much of the argument is necessarily involved in the semantics of attention rather than in the physical, biological and mental processes that

we seek to understand.

A good definition of attentional capture needs to address several key concerns. First of all it needs to be decided if consciousness should play a part in the definition. William James claimed that "*Focalization, concentration, of consciousness are of its essence"*, but since that point consciousness has been found to be a limited and possibly unimportant slice of mental life. The phenomenon of blindsight, in which visual stimuli that are not consciously perceived are still capable of influencing behavior, suggests that attention is more important to consciousness than consciousness is to attention. This brings the question to whether attentional capture necessarily affects behavior, and if so, what would count as behavior. In many models of visual information processing, attention is assumed to be a serial process that utilizes limited computational resources and follows a stage of automatic and preattentive parallel mapping. While this view has been useful, since it is relatively cheap and easy to measure behavioral differences, behavioral paradigms suffer the flaw that overt behavioral responses reflect a multitude of cognitive processes in addition to attentional capture. Opposite this issue is the case in which it is impossible to detect behavioral differences, due either to the structure of the paradigm or the sensitivity of the measurement apparatus. While we may not always be able to detect it or separate it from other costs, it seems fairly certain that any definition of attentional capture needs to account for the use of some limited resource, though it remains unclear what constitutes this resource. Another way of accounting for this use of resources has been to understand it in terms of brain activity. However, given the complexity of the brain and the limitations of electrophysiology, we

are not able to define a threshold at which attention is captured. As technology progresses we will gain increasing resolution of the early visual processing systems, but with each new nuance discovered, another possible definition of attention capture is created. Ultimately we must decide what separates the function of attention capture from the cognitive processes that surround it.

Concluding Remarks

Despite the concerns of definition, the results of our research are far from frivolous. Our findings are consistently observed across a series of experiments, though there is room for numerous interpretations. We set out to explore the workings of involuntary attention capture, pitting a strong top-down control setting against a salient singleton display, using both behavioral and electrophysiological measures. The two major theories of exogenous attention, the contingent capture hypothesis and stimulus salience hypothesis, each made strong predictions as to what results we should have found. Contingent capture suggested our experiment would find a cue validity effect and an N2pc to the relevant cue alone, while stimulus salience proposed that the salient singleton cue would produce a cue validity effect and an N2pc, regardless of relevance. That our results provided evidence both for and against each hypothesis is a testament to the nuance and complexity of our visual attention systems. Only the relevant cue produced both a cue validity effect and a strong N2pc, supporting the contingent capture hypothesis, however the finding of a diminished but significant N2pc to the irrelevant cue supports the stimulus salience hypothesis. This finding, particularly the electrophysiology, highlights an interplay between top-down and bottom-up factors.

Regardless of whether the N2pc is composed of multiple components or whether the N2pc is simply modulated by stimulus relevancy, the results of the present study suggest that capture is a result of the interdependence of relevance and salience.

Bibliography

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception and Psychophysics, 55,* 485-496.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97,* 523-547.

Cave, K. R., & Wolf, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology, 22,* 225-271.

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalograpy and Clinical Neurophysiology*, *99,* 225-234.

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience, 20,* 1423-1433.

Eimer, M., Kiss, M., Press, C., & Sauter, D. (2009).The roles of feature-specific task set and bottom-up salience in attentional capture: An ERP study. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1316-1328.

Folk, C. L., & Remington, R. W. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 847-858.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1030-1044.

Gibson, B.S., & Peterson, M.A. (2001). Inattentional blindness and attentional capture: Evidence for attention-based theories of visual salience. In C.L. Folk & B.S. Gibson

(Eds.), *Attraction, Distraction, and Action: Interdisciplinary Perspectives on Attentional Capture.* Elsevier: Oxford, UK.

Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience.* **21**, 760-775.

Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience, 18,* 604-613.

Leber, A. B., & Egeth, H. E. (2006). It's under control: Top-down search strategies can override attentional capture. *Psychonomic Bulletin & Review, 13 (1),* 132-138.

Lien, M.-C., Ruthruff, E., & Cornett, L. (2010). Attentional capture by singletons is contingent on top-down control settings: Evidence from electrophysiological measures. *Visual Cognition, 18,* 682-727.

Lien, M.-C., Ruthruff, E., Goodin, Z., & Remington, R. W. (2008). Contingent attentional capture by top-down control settings: Converging evidence from event-related potentials. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 509-530.

Luck, S. J. (2005). *An introduction to the event-related potential technique.* Cambridge, MA: MIT Press.

Luck, S. J., & Hillyard, S. A. (1990). Electrophysiological evidence for parallel and serial processing during visual search. *Perception and Psychophysics*, *48,* 603-617.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human*

Perception and Performance, *20*, 1000-1014.

Mazza, V., Turatto, M., & Caramazza, A (2009). Attention selection, distractor suppression and N2pc. *Cortex, 45,* 879-890.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3-25.

Remington, R. W., Folk, C. L., & McLean, J. P. (2001). Contingent attentional capture or delayed allocation of attention? *Perception and Psychophysics, 63,* 298-307.

Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. *Attention, Perception, & Psychophysics, 72,* 1455-1470.

Theeuwes, J. (1991). Exogenous and endogenous control of attention: The effect of visual onsets and offsets. *Perception and Psychophysics, 49,* 83-90.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception and Psychophysics, 51,* 599-606.

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: Selective search for color and visual abrupt onsets. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 799-806.

Theeuwes, J. (2004). Top-down search strategies cannot override attentional capture. *Psychonomic Bulletin & Review, 11,* 65-70.

Theeuwes, J., Atchley, P., & Kramer, A. F. (2000). On the time course of top-down and bottom-up control of visual attention. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII (pp. 105-124)*. Cambridge. MA: MIT Press.

Verbruggen, F., & Logan, G. D. (2008). Automatic and controlled response inhibition: Associative learning in the go/no-go and stop-signal paradigms. *Journal of Experimental Psychology: General, 137*, 649-672.

Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 121-138.

Woodman, G.F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature, 400,* 867-869.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 601-621.

Table 1

Mean Response Times in Milliseconds (Standard Error of Means in Parentheses) for the Go Trials as a Function of Singleton Cue Type (Relevant vs. Irrelevant) and Cue Validity (Valid vs. Invalid) in Experiments 2-5.

Singleton Cue Type	*Cue Validity*		Cue Validity Effect
	Valid	Invalid	
	Experiment 2		
Relevant	535 (9)	584 (9)	*49 (4)*
Irrelevant	570 (12)	574 (10)	*5 (6)*
	Experiment 3		
Relevant	551 (14)	587 (15)	*36 (6)*
Irrelevant	576 (15)	582 (14)	*6 (3)*
	Experiment 4		
Relevant	574 (15)	626 (18)	*52 (7)*
Irrelevant	610 (15)	618 (16)	*8 (4)*
	Experiment 5		
Relevant	563 (18)	612 (21)	*49 (8)*
Irrelevant	590 (21)	596 (21)	*6 (5)*

Table 2

Proportion of Errors (Standard Error of Means in Parentheses) for the Go Trials as a Function of Singleton Cue Type (Relevant vs. Irrelevant) and Cue Validity (Valid vs. Invalid) in Experiments 2-5.

Singleton Cue Type	*Cue Validity*		Cue Validity Effect
	Valid	Invalid	
	Experiment 2		
Relevant	.008 (.002)	.017 (.003)	*.009 (.002)*
Irrelevant	.008 (.004)	.015 (.003)	*.007 (.004)*
	Experiment 3		
Relevant	.018 (.007)	.033 (.005)	*.015 (.007)*
Irrelevant	.014 (.005)	.022 (.006)	*.008 (.004)*
	Experiment 4		
Relevant	.024 (.008)	.033 (.005)	*.009 (.008)*
Irrelevant	.027 (.005)	.036 (.007)	*.008 (.005)*
	Experiment 5		
Relevant	.021 (.008)	.045 (.009)	*.024 (.008)*
Irrelevant	.023 (.006)	.036 (.006)	*.013 (.005)*

Figure Captions

Figure 1. A hypothetical N2–posterior– contralateral (N2pc) component produced when attention is allocated to a stimulus (the filled dots in this case) in the left visual field (Panel A) or the right visual field (Panel B). Roughly 200–300 ms after stimulus onset, the event-related potentials are more negative for posterior electrode sites contralateral to the stimulus location than ipsilateral to the stimulus location. The N2pc effect (represented by the shaded region) is defined as the difference in amplitude between the contralateral and ipsilateral waveforms. Negative is plotted upward, and time zero represents stimulus onset.

Figure 2. An example event sequence for the red target (Go trials) in Experiments 1-5. In the real experiment, the stimuli were colored. Panel A (Experiment 1) shows an example of the capture cue display containing all white boxes (neutral cue). In the target display, the top-left letter "T" was red and others were white. Panel B (Experiments 2 and 3) shows an example of the capture cue display, where the top-left box was green and others were white (irrelevant singleton cue). Panel C (Experiment 4) shows an example of the target display, where the top-left letter "T" was red, the top-right letter "L" was blue, and others were white. Panel D (Experiment 5) shows an example of the target display, where the top-left letter "T" was red, the top-right letter "L" was blue, the bottom-left letter "L" was yellow, and the bottom-right letter "T" was white.

Figure 3. Grand average N2pc difference waveforms averaged across the P5/P6, O1/O2, and PO5/PO6 electrode pairs for Go trials and No-go trials in Experiment 1. The N2pc difference waveforms were calculated by subtracting the ipsilateral potentials from contralateral potentials (with respect to the target location). The baseline period was the 200 ms prior to the neutral cue display onset. Negative is plotted upward and time zero represents singleton cue onset. Target onset occurred 150 ms after singleton cue onset. The unfilled rectangular box indicates the time window used to assess the target-elicited N2pc effect: 350-450 ms after the neutral cue display onset (200-300 ms after target onset). The bottom of the figure shows the scalp topography of the overall average waveforms during the time window 350-450 ms after the neutral cue onset for go and no-go trials.

Figure 4. Grand average N2pc difference waveforms averaged across the P5/P6, O1/O2, and PO5/PO6 electrode pairs as a function of the singleton cue type (relevant vs. irrelevant) and whether the singleton cue and the target were in the same hemifields or different hemifields for Go trials and No-go trials in Experiment 2. The N2pc difference waveforms were calculated by subtracting the ipsilateral potentials from contralateral potentials (with respect to the singleton cue location). The baseline period was the 200 ms prior to singleton cue onset. Negative is plotted upward and time zero represents

singleton cue onset. Target onset occurred 150 ms after singleton cue onset. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 150-250 ms after cue onset (for the singleton-elicited N2pc effect) and 350-450 ms after cue onset (for the target-elicited N2pc effect).

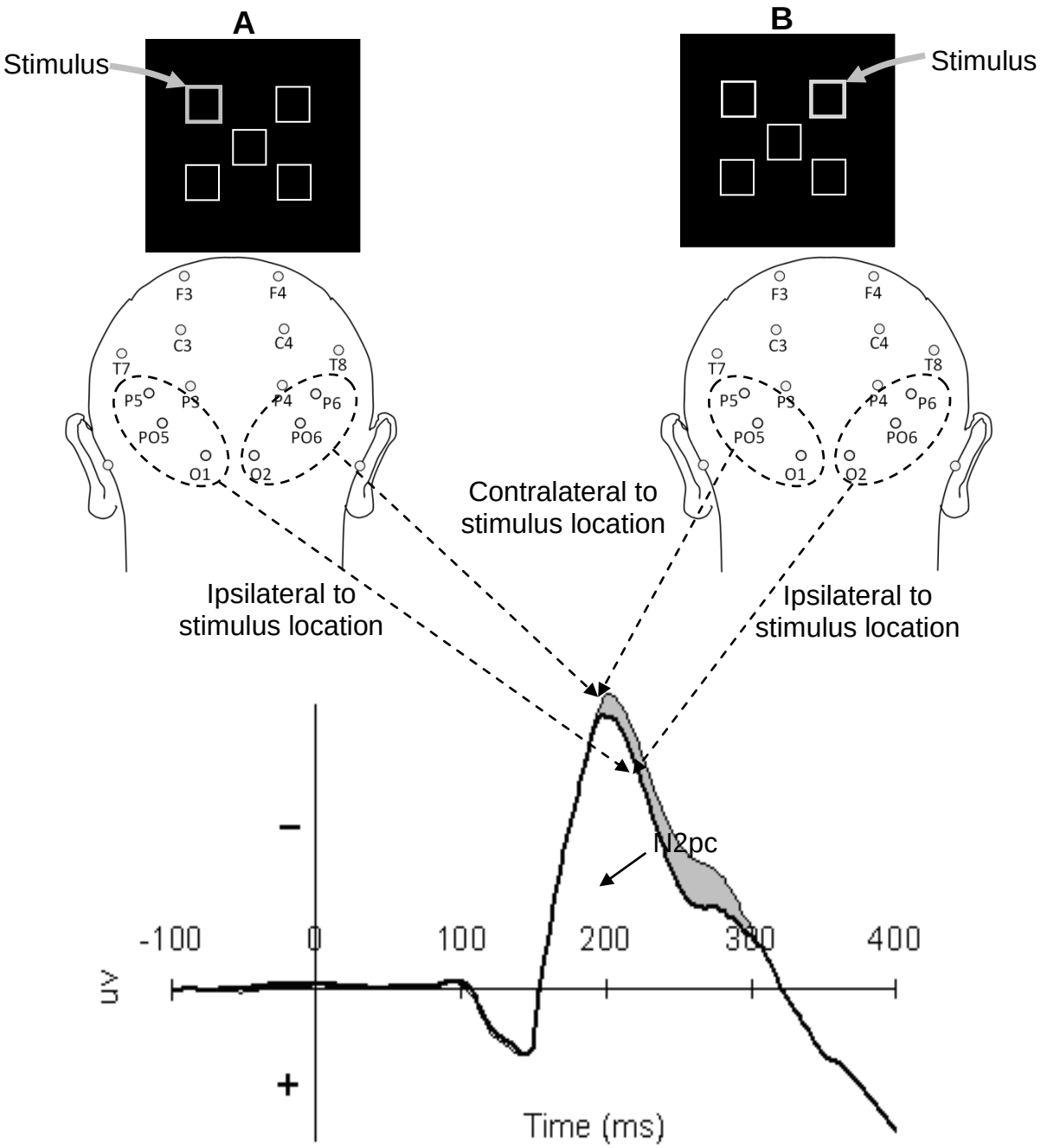
Figure 5. Grand average N2pc difference waveforms averaged across the P5/P6, O1/O2, and PO5/PO6 electrode pairs as a function of the singleton cue type (relevant vs. irrelevant) and whether the singleton cue and the target were in the same hemifields or different hemifields for Go trials and No-go trials in Experiment 3. The N2pc difference waveforms were calculated by subtracting the ipsilateral potentials from contralateral potentials (with respect to the singleton cue location). The baseline period was the 200 ms prior to singleton cue onset. Negative is plotted upward and time zero represents singleton cue onset. Target onset occurred 150 ms after singleton cue onset. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 150-250 ms after cue onset (for the singleton-elicited N2pc effect) and 350-450 ms after cue onset (for the target-elicited N2pc effect).

Figure 6. Grand average N2pc difference waveforms averaged across the P5/P6, O1/O2, and PO5/PO6 electrode pairs as a function of the singleton cue type (relevant vs. irrelevant) for Go trials and No-go trials in Experiment 4. For the Go trials, the data were also plotted as a function of whether the singleton cue and the target were in the same hemifields or different hemifields. The N2pc difference waveforms were calculated by subtracting the ipsilateral potentials from contralateral potentials (with respect to the singleton cue location). The baseline period was the 200 ms prior to singleton cue onset. Negative is plotted upward and time zero represents singleton cue onset. Target onset occurred 150 ms after singleton cue onset. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 150-250 ms after cue onset (for the singleton-elicited N2pc effect) and 350-450 ms after cue onset (for the target-elicited N2pc effect).

Figure 7. Grand average N2pc difference waveforms averaged across the P5/P6, O1/O2, and PO5/PO6 electrode pairs as a function of the singleton cue type (relevant vs. irrelevant) for Go trials and No-go trials in Experiment 5. For the Go trials, the data were also plotted as a function of whether the singleton cue and the target were in the same hemifields or different hemifields. The N2pc difference waveforms were calculated by subtracting the ipsilateral potentials from contralateral potentials (with respect to the singleton cue location). The baseline period was the 200 ms prior to singleton cue onset. Negative is plotted upward and time zero represents singleton cue onset. Target onset occurred 150 ms after singleton cue onset. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 150-250 ms after cue onset (for the singleton-elicited N2pc effect) and 350-450 ms after cue onset (for the

target-elicited N2pc effect).

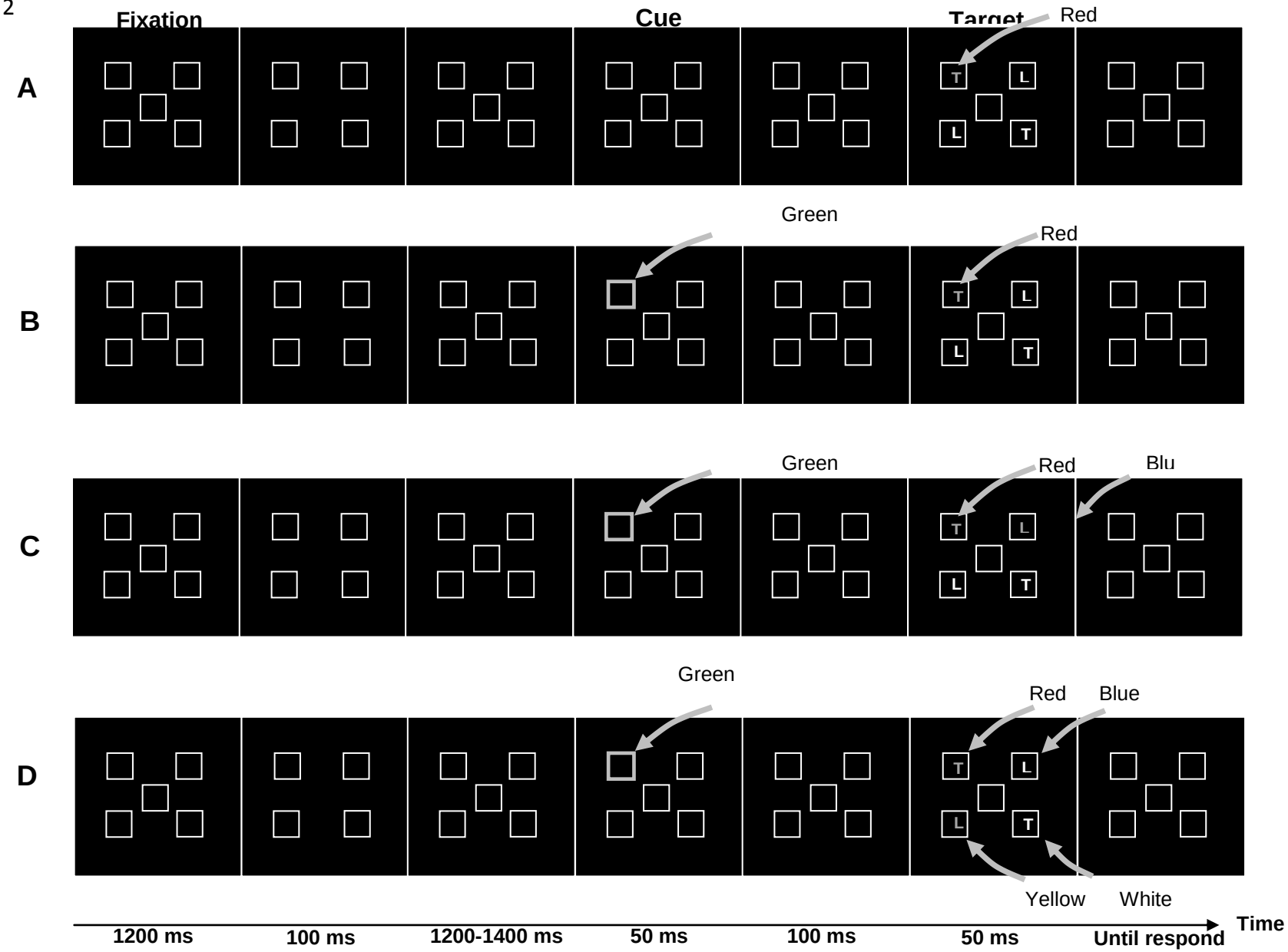
Figure 1



Contralateral to stimulus location

Ipsilateral to stimulus location

Figure 2


Fixation
Cue
Target
Red
A
Green
Red
B
Green
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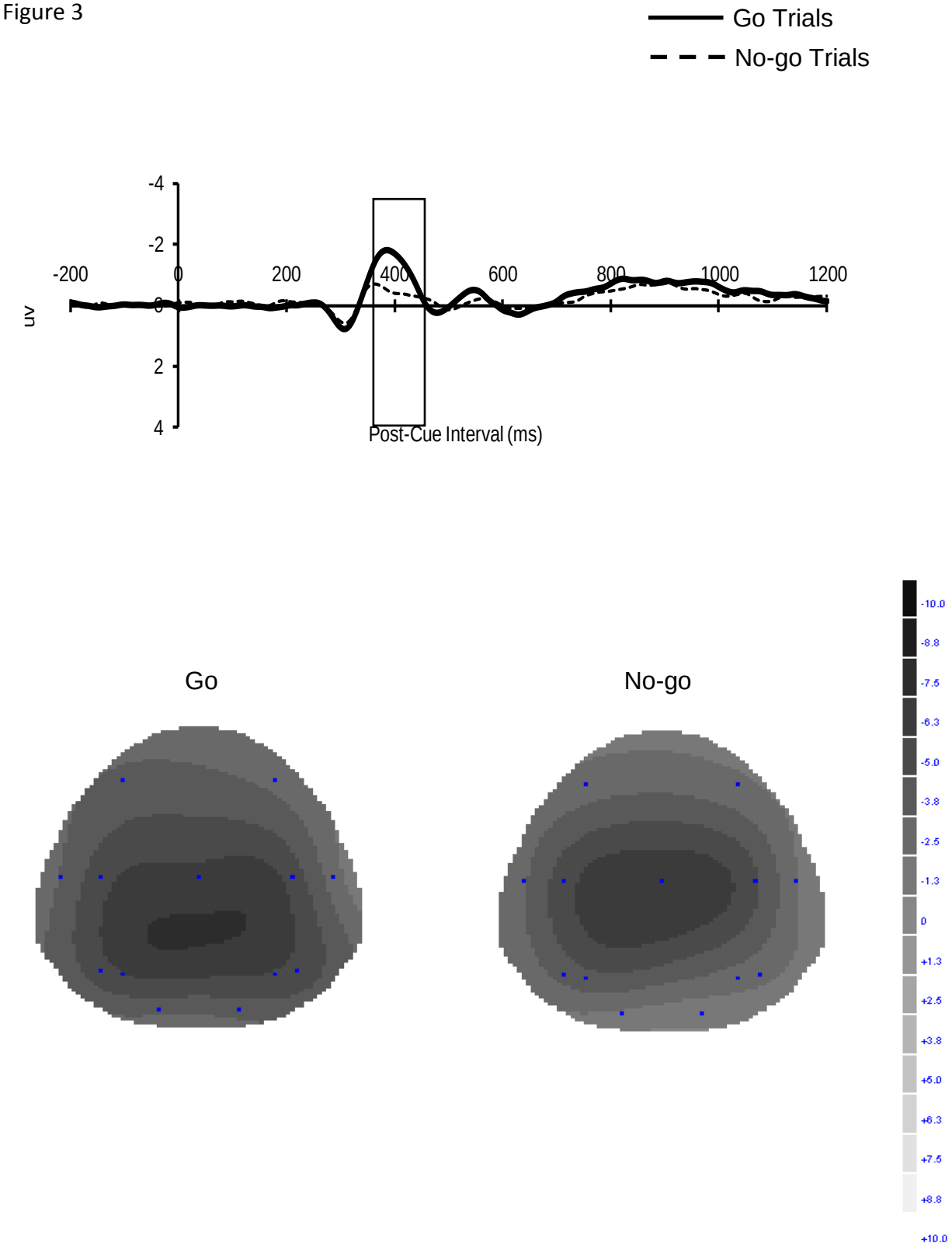
C
Green
Red
Blue
D
Yellow
White
1200 ms
100 ms
1200-1400 ms
50 ms
100 ms
50 ms
Until respond
Time

Figure 3


Go Trials
No-go Trials
-4
-2
0
2
4
uv
-200
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400
600
800
1000
1200
Post-Cue Interval (ms)
Go
No-go
-10.0
-8.8
-7.5
-6.3
-5.0
-3.8
-2.5
-1.3
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+6.3
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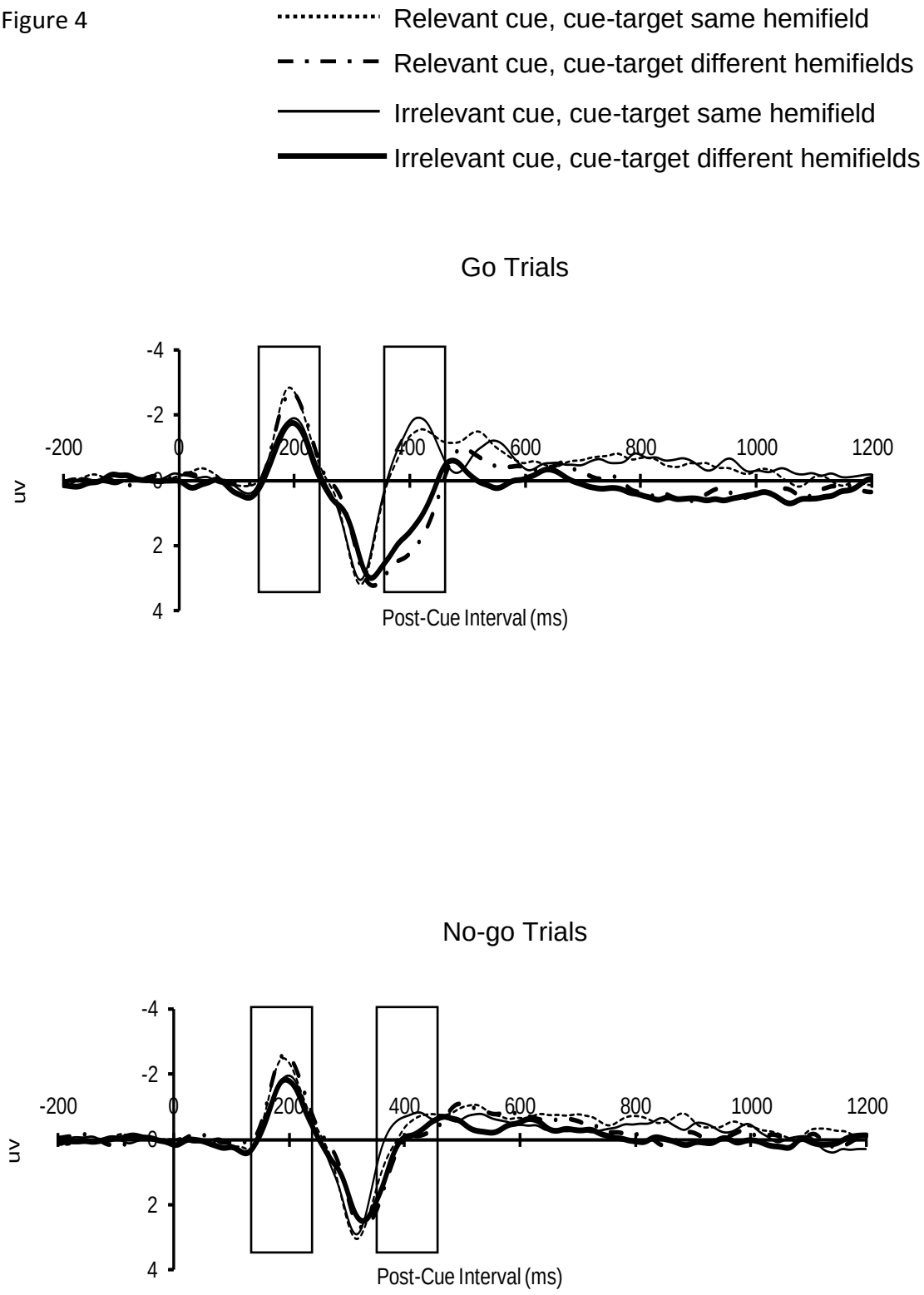
+8.8
+10.0

Figure 4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Relevant cue, cue-target different hemifields
Irrelevant cue, cue-target same hemifield
Irrelevant cue, cue-target different hemifields
Go Trials
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uv
-200
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200
400
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800
1000
1200
Post-Cue Interval (ms)
No-go Trials
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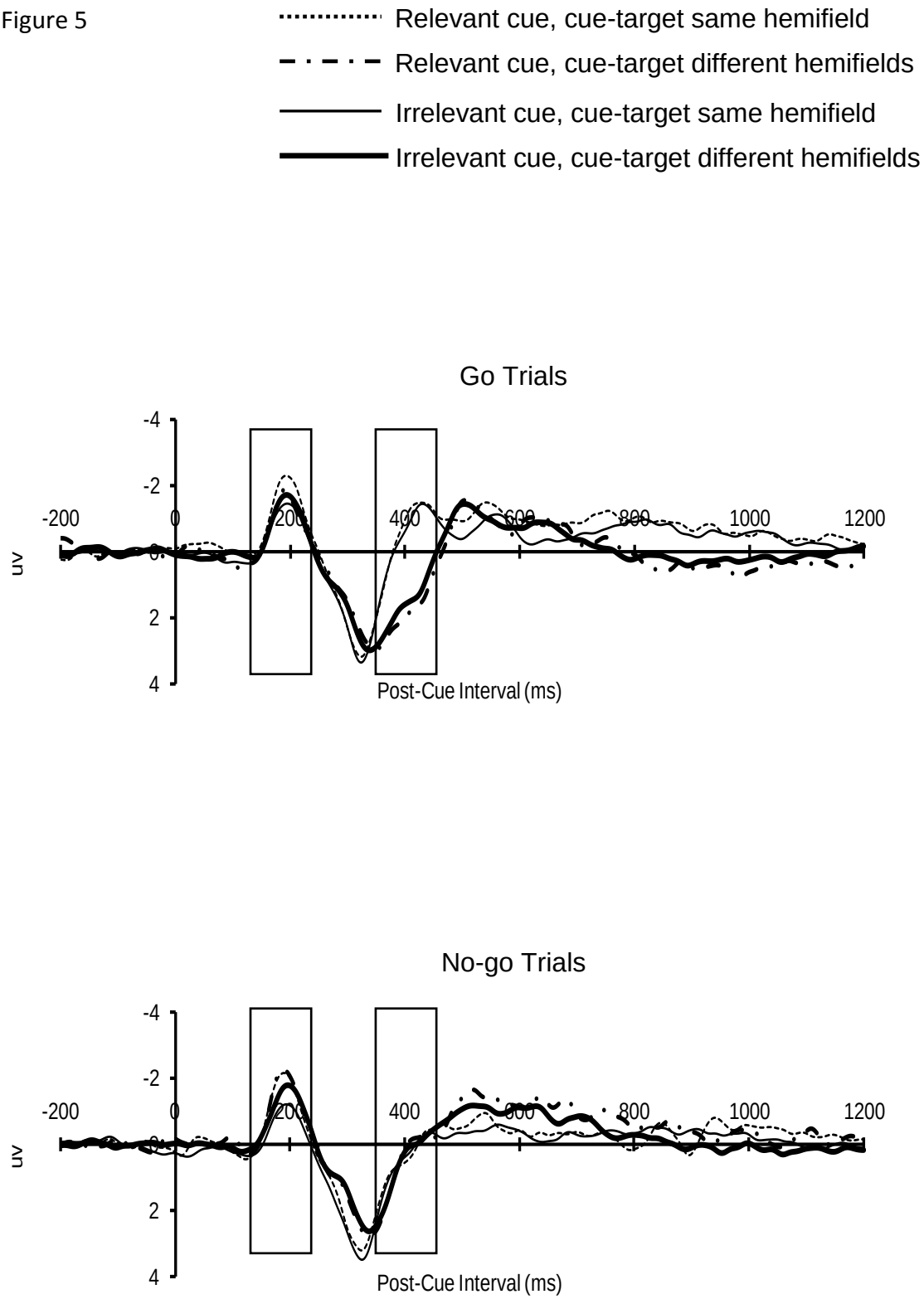
1200
Post-Cue Interval (ms)

Figure 5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Relevant cue, cue-target different hemifields
Irrelevant cue, cue-target same hemifield
Irrelevant cue, cue-target different hemifields
Go Trials
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Post-Cue Interval (ms)
No-go Trials
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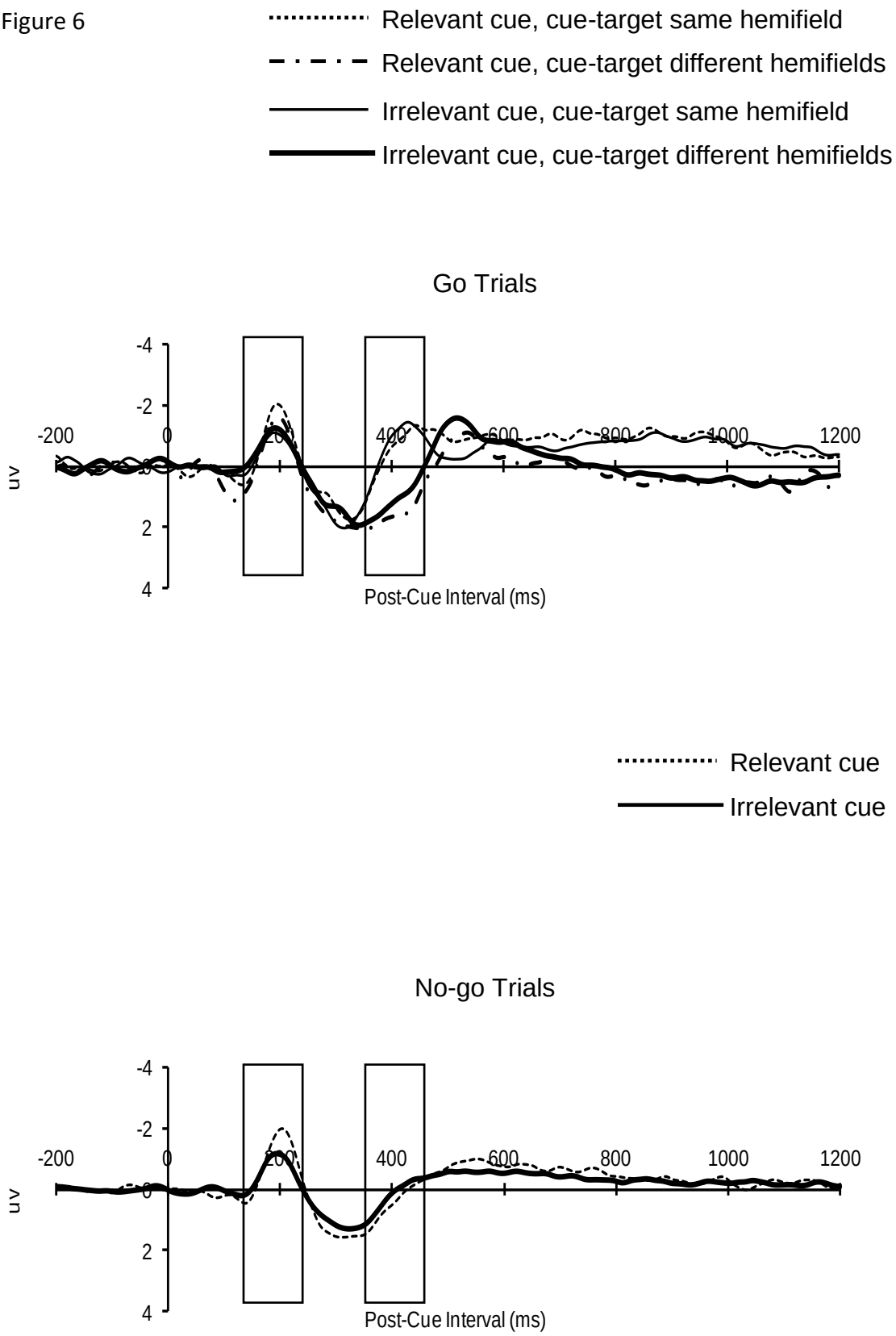
4
Post-Cue Interval (ms)

Figure 6


Relevant cue, cue-target same hemifield
Relevant cue, cue-target different hemifields
Irrelevant cue, cue-target same hemifield
Irrelevant cue, cue-target different hemifields
Go Trials
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Post-Cue Interval (ms)
Relevant cue
Irrelevant cue
No-go Trials
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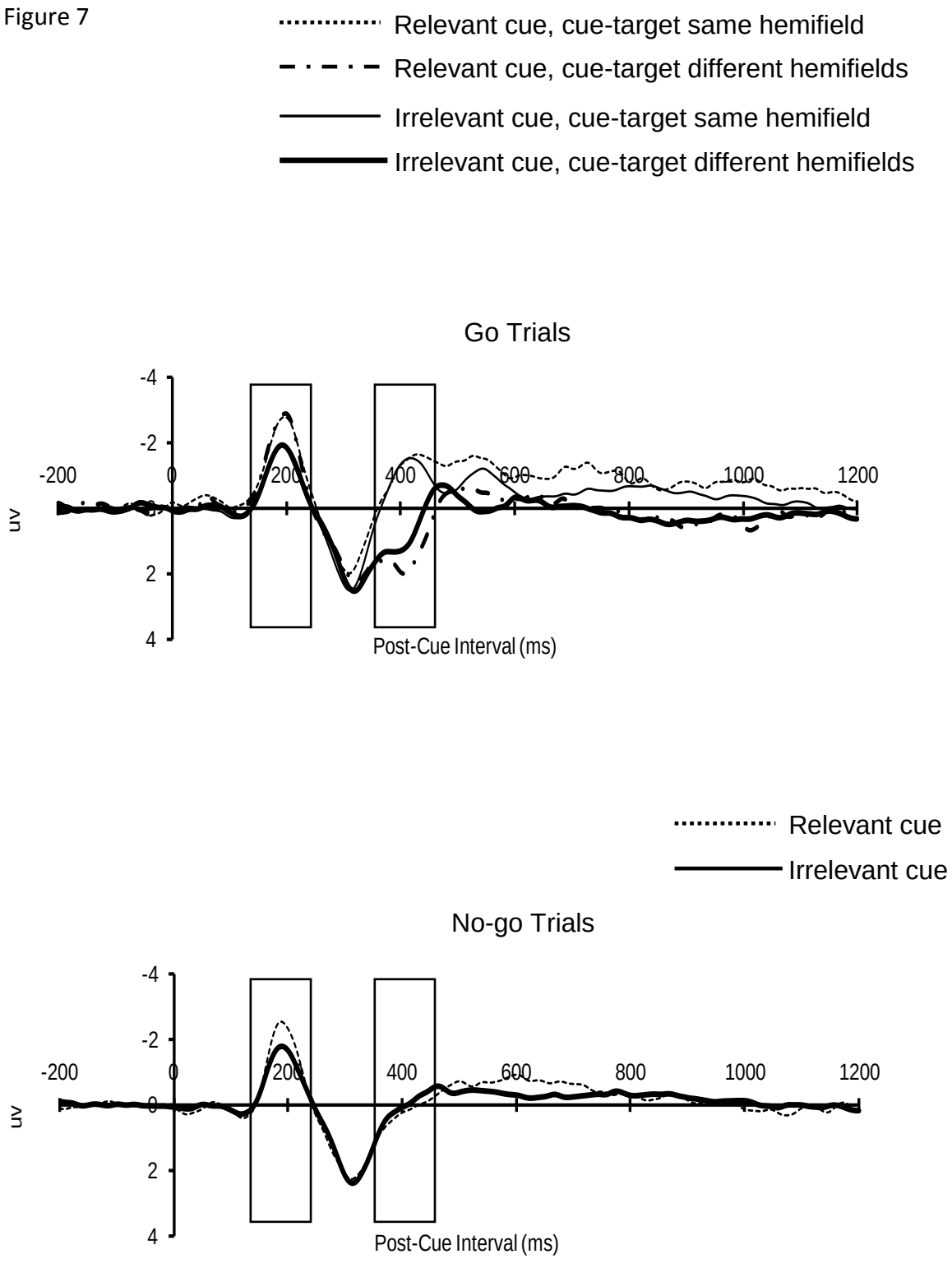
4
Post-Cue Interval (ms)

Figure 7


Relevant cue, cue-target same hemifield
Relevant cue, cue-target different hemifields
Irrelevant cue, cue-target same hemifield
Irrelevant cue, cue-target different hemifields
Go Trials
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Post-Cue Interval (ms)
Relevant cue
Irrelevant cue
No-go Trials
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Post-Cue Interval (ms)