# *An Electrophysiological Study of Attention Capture by Salience: Does Rarity Enable Capture?*





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# An Electrophysiological Study of Attention Capture by Salience: Does Rarity Enable Capture?

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**Abstract**

Several behavioral studies have suggested that rarity is critical for enabling irrelevant, salient objects to capture attention. We tested this hypothesis using the N2pc, thought to reflect attentional allocation. A cue display was followed by a target display in which participants identified the letter in a specific color. Experiment 1 pitted rare, irrelevant abrupt onset cues (appearing on only 20% of trials) against target-relevant color cues. The relevant color cue produced large N2pc and cue validity effects, even when competing with a rare, salient, simultaneous abrupt onset. Similar results occurred even when abrupt onset frequency was reduced to only 10% of trials (Experiment 2). Experiment 3 examined rare, irrelevant color singleton cues (20% of trials). Despite being rare and salient, these singleton cues produced no N2pc or cue validity effect, indicating little attentional capture. Experiment 4 greatly increased color cue salience by adding 4 background boxes, increasing color contrast, and tripling the cue display duration (from 50 to 150 ms). Small cue validity and N2pc effects were obtained, but did not strongly depend on degree of rarity (20% vs. 100%). We argue that rarity by itself is neither necessary nor sufficient to produce attention capture.

**An Electrophysiological Study of Attention Capture by Salience:**

**Does Rarity Enable Capture?**

The capture of spatial attention by important objects in visual scenes is critical in the real world. It allows us to rapidly evaluate and respond to important stimuli, such as road hazards. Often, our attention is summoned by objects with no apparent relevance to our current goals (e.g., capture by banner ads when trying to read a news article on the web). At other times, we completely fail to notice obvious objects in the scene (e.g., while distracted, failing to notice that the approaching stoplight has changed from green to red). Given these seemingly contradictory tendencies and the high importance of capture for information processing, researchers have attempted to uncover the conditions necessary for capture to occur (e.g., Yantis, 2000).

Over the last 20 years, studies of attention capture have focused on a battle between two opposing views. The *salience capture* view suggests that the ability to capture attention is primarily determined by stimulus salience (e.g., Hickey, McDonald, & Theeuwes, 2006; Theeuwes, 1994). That is, the salient object in a scene (e.g., an abrupt onset against a static background or a color singleton against a homogeneously-colored background) is assumed to capture our attention involuntarily even when it has no properties that the observer is looking for at that moment. The *contingent capture* view, on the other hand, contends that capture is primarily driven by top-down control settings (e.g., Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, Goodin, & Remington, 2008). Accordingly, salient stimuli do not capture attention involuntarily if they are truly irrelevant; instead, only objects containing target-defining features have the ability to capture attention.

In most studies supporting the contingent capture view, the irrelevant, salient stimuli were presented relatively often throughout the experiment (e.g., at least 50% of the trials and

often 100%; e.g., Bacon & Egeth, 1994; Folk et al., 1992; Lien et al., 2008). This point raises an interesting alternative hypothesis: perhaps salient stimuli normally capture attention strongly, but inhibition is eventually invoked when a salient stimulus repeatedly appears in the visual field (e.g., Becker & Horstmann, 2011; Forster & Lavie, 2011; Gibson & Jiang, 1998; Godijn & Kramer, 2008; Horstmann, 2002; Horstmann & Ansorge, 2006; Neo & Chua, 2006; Yantis & Egeth, 1999). Tests of this hypothesis have reached conflicting conclusions which, as discussed below, might reflect limitations in the use of behavioral measures of capture (but see the oculomotor measure in Godjin & Kramer, 2008). The present study aims to shed additional light on capture by rarity using a more direct, electrophysiological measure of capture.

Before addressing research on attention capture by irrelevant, rare objects, it is important to make an explicit distinction between capture by surprise and capture by rarity. Studies on capture by surprise have primarily focused on the capture effect by the first encounter of an unexpected, surprising object. Studies of rarity, in contrast, manipulate the frequency of a particular salient stimulus, with the capture averaged across the set of trials in which rare objects appeared. The focus of the present research is on the latter issue – capture by rare stimuli – though we will briefly review research on both issues.

## Capture by Surprise

Studies on whether surprising objects capture attention in a purely stimulus-driven manner have revealed somewhat conflict findings (e.g., Gibson & Jiang, 1998; Horstmann, 2002, 2005; Horstmann & Becker, 2008). For instance, Gibson and Jiang (1998) used a visual search paradigm in which participants searched for the letter H or U amongst 8 letters in a circular array, presented for only 86 ms and then masked for 200 ms. These target letters were not distinguishable from other distractor letters based on color (they were all white) for the first 192

experimental trials. Thus, there was no incentive to search for a specific feature discontinuity (i.e., singleton). The critical manipulation was on Trial 193, where the target letter was an unexpected red color singleton among white distractors. This unexpected trial was followed by another 192 trials in which the target letters were always color singletons (i.e., red). Gibson and Jiang measured target detection accuracy. They reasoned that if attention capture is solely driven by stimulus salience, then the unexpected color singleton should capture attention on Trial 193 and therefore be detected just as accurately as it was on the subsequent trials (i.e., where participants presumably had learned to search for the color singleton). In contrast to this prediction, they found that the accuracy for the unexpected trial was lower than the color-singleton-defined target trials (the last 192 trials). In fact, accuracy on this critical trial was not even better than the accuracy observed from the first 192 trials where the target was not a color singleton. These findings led Gibson and Jiang to conclude that the unexpected color singleton did not capture attention.

Nevertheless, it is possible that salient, unexpected objects capture attention initially but the sudden appearance of this discrepant stimulus also interrupts the current goal-driven behavior, requiring re-establishment of the task set and thereby delaying responses (see Woods & Patterson, 2001). So the costs and benefits of capture might offset. To demonstrate capture by unexpected objects without contamination from the cost of reestablishing task set, Horstmann (2002) adopted Gibson and Jiang's (1998) single-unexpected trial approach but presented the unexpected color singleton either 500 ms before or simultaneously with the target display (i.e., the stimulus onset asynchrony [SOA] was 500 ms or 0 ms). Similar to Gibson and Jiang, Horstmann (2002) found no improvement in accuracy on the surprise trial in the simultaneous condition. However, an improvement was found when the singleton appeared 500 ms before the

target display. In fact, accuracy in this condition was just as high as it was in the subsequent color-singleton-defined target trials. Horstmann argued that surprising objects capture attention strongly, but the shift of attention takes time. However, one caution regarding this conclusion should be noted. Several authors have suggested that the relatively long SOAs between the cue and the target may have been sufficient for an endogenous shift of attention, even without any capture per se (e.g., Theeuwes, Atchely, & Kramer, 2000; Theeuwes, Godijn, & Pratt, 2004).

## Capture by Rarity

While examining capture by surprising objects using a single-trial method had some advantages, it also has some limitations, as described above. Taking a different approach, other researchers manipulated the frequency of irrelevant, salient objects and examined capture by rarely occurring objects. For instance, Yantis and Egeth (1999; Experiment 9) had participants searched for a vertical target among several tilted distractors. One of the distractors was a color singleton (red among all blue) for 80% of the trials for the "frequent" group and for only 20% of the trials for the "rare" group. All participants were informed that the color singleton would never be the target; thus, there was no incentive to allocate attention to the salient color singleton. Instead of measuring accuracy, as in studies of surprise capture, they measured response time (RT). Yantis and Egeth reasoned that if a salient color singleton captures attention in a purely bottom-up manner, then the presence of an irrelevant color singleton should impair performance (i.e., slow RT). In addition, this singleton cost should be larger for the rare group than the frequent group. In contrast to these predictions, RT was equivalent between the singleton present and absent trials in both the frequent and rare groups. These findings led Yantis and Egeth to conclude that rare color singletons do not have the inherent power to capture spatial attention, supporting Gibson and Jiang's (1998) conclusion.

Horstmann and Ansorge (2006) examined capture by color singletons that were even more rare (4%, 8%, or 11%) than those in Yantis and Egeth (1999; 20%). In addition to using various SOAs between the onsets of color singleton and the target (0, 200, and 400 ms), the color singleton was predictive of the target location (the target singleton block) or a non-target location (the distractor singleton block). Participants were informed regarding the predictability and frequency of the color singleton. The critical finding was that the degree of singleton rarity (4%, 8%, or 11%) had virtually no effect on the benefit or cost of the singleton on target performance.

Whereas the studies above examined capture by rare color singletons, Neo and Chua (2006) examined capture by rare abrupt onsets. Attention was prioritized to the target location by using a 100% valid arrow cue (Experiments 1 and 2), or by presenting the target in a fixed location (Experiment 3), so participants were fully aware of where the target would appear. On some trials, an irrelevant abrupt onset appeared 60 ms or 200 ms before the target (i.e., SOA was 60 or 200 ms) in a non-target location. In Experiment 1, with an abrupt onset on 75% of the trials, onsets had little effect on RT at both SOAs, suggesting a failure to capture attention. However, as the frequency of an abrupt onset decreased to only 18.75% in Experiment 2, RT was 30 ms longer in the onset condition than the no-onset condition at the 200-ms SOA. Their findings argue for capture by rare abrupt onsets, even when attention has been prioritized to another location (see also Forster & Lavie, 2011).

## The Present Study

The studies on capture by rare, salient objects reviewed above are inconclusive regarding capture by rare objects. This may be because the use of behavioral measures (e.g., accuracy or overall RT) limits the ability to detect rapid capture of spatial attention. For example, costs and benefits of capture on RT can roughly cancel each other out, as shown in Horstmann (2002).

Shifts can happen too quickly (followed by disengagement) or too slowly to affect RT (e.g., Belopolsky, Schreij, & Theeuwes, 2010). Furthermore, when RT costs do occur, they can reflect not only involuntary capture but also other phenomena, such as voluntary attention shifts or filtering costs (e.g., Remington, Folk, & McLean, 2001).

To overcome these limitations, the present study supplemented traditional behavioral measures with electrophysiological measures (e.g., event-related potentials [ERPs]). ERPs can provide a continuous measure of attentional shifts. Thus, they have the potential to detect a rapid, temporary shift of attention by salient stimuli even when they occur too early or too late to influence overt behavior (see Handy, Green, Klein, & Mangun, 2001, for an excellent example of uncovering attentional processes using ERP measures). It should be emphasized that we used ERP measures to study capture by rarity, not capture by surprise, due to the limitations of collecting and interpreting ERP measures on a single trial (i.e., low signal-noise ratio).

We used the ERP component called the *N2pc effect* (short for N2-posterior-contralateral) to determine whether attention can be captured by irrelevant, salient objects when they appear rarely. The N2pc effect is known to reflect shifts of spatial attention (e.g., Luck & Hillyard, 1994; Woodman & Luck, 2003). This component is an increased negativity over posterior scalp contralateral to an attended stimulus, peaking about 170-270 ms after the onset of that stimulus. In other words, the ERP at a given electrode in the right hemisphere becomes more negative when attention is directed to a left-hemifield stimulus (contralateral) than to a right-hemifield stimulus (ipsilateral), and vice versa. The N2pc effect, therefore, can be quantified as the average difference between contralateral and ipsilateral voltage. In contrast to the coarse information provided by behavioral measures, the N2pc effect can provide both temporal (when) and spatial (where) information regarding an attentional shift, and has been widely used as a

sensitive and specific index of attention capture in recent years (e.g., Eimer & Kiss, 2008; Hickey et al., 2006; Lien et al., 2010; Lien et al., 2008; Sawaki & Luck, 2010).

We used a cuing paradigm in which the cue display was presented prior to the target display. We chose an SOA of 150 ms (a typical interval used in previous attentional capture studies using the cuing paradigm; e.g., Folk et al., 1992; Lien et al., 2008; but see Experiment 4 below), so that there was not enough time for an endogenous shift of attention or a saccade. This temporal isolation of the cue and target events also enables us to measure cue validity effects in the behavioral data. Most important, it helps to minimize overlap between cue- and target-elicited N2pc effects and also gives the cue the opportunity to capture attention without simultaneously competing for attention with the target.

Experiment 1 examined capture by a salient abrupt onset when it appeared on only 20% of trials, a frequency similar to that used in previous studies of stimulus rarity (e.g., Neo & Chua, 2006; Yantis & Egeth, 1999). Experiment 2 further reduced the frequency of abrupt onsets to only 10%. Experiments 3 and 4 examined capture by irrelevant color singleton cues, instead of abrupt onsets.

## Experiment 1

Experiment 1 examined whether a salient-but-irrelevant abrupt onset has the power to capture spatial attention, producing N2pc and cue validity effects, when it appears rarely. We cannot directly assess attention capture by abrupt onsets using the N2pc effect because the mere presence of the new object in one hemifield would create a lateralized imbalance in stimulus energy, thereby triggering lateralized ERPs even if it did not capture spatial attention (see Lien et al., 2008; Sawaki & Luck, 2010, for further discussion regarding eliminating sensory confounds in ERP designs). Because there is no way to know whether the measured N2pc effect elicited by

the abrupt onset itself was due to sensory or attentional influences, it cannot be meaningfully interpreted. To get around the inability to directly measure the N2pc effect to an abrupt onset, we used the approach of Lien et al. (2008; Experiment 3) and measured the indirect influence of the abrupt onset on capture by a relevant color cue. In other words, we pitted an abrupt onset against a relevant color cue; the critical analysis was a comparison of the N2pc effect by the relevant color cue with and without the simultaneous abrupt onsets.

For the cue display, 80% of the trials contained a relevant color singleton cue (i.e., a box in the target color amongst several boxes in a homogenous distractor color). On the remaining 20% of the trials, an abrupt onset (four dots surrounding one of the distractor color boxes) appeared simultaneously with the relevant color singleton cue. The abrupt onset appeared in the same hemifield as the relevant color singleton cue on 10% of the trials (but never in the same location) and appeared in the different hemifield on the other 10% of the trials (see Figure 1, Panel A). To ensure that the relevant cue was a color singleton in all trials, we colored the abrupt onset in the same color as the background distractor boxes. The relevant color singleton cue did not predict the target location (25% valid vs. 75% invalid), nor did the abrupt onset. Therefore, participants had no incentive to voluntarily shift attention to the relevant cue or the abrupt onset. It is important to note that two aspects of the design in this experiment were different from Lien et al. (2008; Experiment 3): in that study, the relevant color cue was never a color singleton and the proportion of abrupt onset trials was higher (50% rather than 20%).

The target display always contained two colored letters and two white letters, all of which were T's and L's (see Figure 2 for an example). Participants were asked to search for a letter in a specific color (red for half of the participants and green for the other half) and press a key to indicate whether it was a T or L. Because there were two colored letters with potential target

identities (T or L), the use of a specific top-down attentional setting (e.g., searching for a specific color) was necessary to perform the task accurately, discouraging use of singleton-detection mode (e.g., Lien et al., 2008). We compared the capture effects (the N2pc and cue validity effects) for the relevant color singleton with and without the abrupt onset.

We expected, based on previous studies, that the relevant color singleton cue would capture attention and thus produce a large N2pc effect and a cue validity effect on RT when it appeared alone. The interesting question was whether the simultaneous, rare abrupt onset would pull attention away from the relevant color singleton cue, diminishing the relevant cue's ability to capture attention and thereby reducing or eliminating its N2pc and cue validity effects. According to the salience capture view, attention is first allocated to the most salient stimulus; in the present case, attention would be allocated first to the abrupt onset, pulling it away from the relevant color cue. If so, the abrupt onset should reduce or even eliminate capture by the relevant color cue (or at least delay its onset).

Although our primary interest was in the cue-elicited N2pc effects, we also examined target-elicited N2pc effects for the sake of completeness. Within a trial, we defined the N2pc effect with respect to the relevant color singleton cue location. Therefore, when the relevant color singleton cue and target are in the same hemifield, the cue and target should produce an N2pc effect in the same direction. When they are in different hemifields, however, the polarity of the N2pc effect elicited by the target should be opposite to that of the color singleton.

## Method

Participants. Nineteen undergraduate students from Oregon State University participated in exchange for extra course credit. Three participants' data were excluded because either their averaged HEOG was larger than ± 3μV during the critical time windows (170-270 ms and 350-

450 ms after the cue onset) or their EEG artifact rejection was more than 25% of trials. Therefore, data from 16 participants (12 females and 4 males) were included in the final data analyses. They had a mean age of 23 years (range: 18-32). Eight participants responded to the red letter and 8 to the green letter. All reported having normal or corrected-to-normal acuity. They also demonstrated normal color vision using the Ishihara Test for color deficiency.

Apparatus and Stimuli. Stimuli, displayed on a 19-inch ViewSonic monitor, were viewed from a distance of about 55 cm. Within each trial, three stimulus events were presented in succession (see Figure 2): the fixation display, cue display, and target display. 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 (7.66º, center to center). Adjacent peripheral boxes were separated by 10.81º, center to center. Each box was 2.39º × 2.39º, drawn with thin (0.10º) white lines.

For 80% of the trials, the cue display was the same as the fixation display except that one peripheral box contained a relevant color (i.e., the color singleton cue) while the other boxes all had the identical distractor color (e.g., for participants assigned to look for the red target, one box would be red and the other boxes would be green). The center box also contained the background, distractor color. On the remaining 20% of the trials, the cue display also contained an abrupt onset: four dots arranged in a diamond configuration around one of the background boxes (each dot was 1.04° in diameter and located 0.31° from the edge of the box). To ensure that the relevant cue was a color singleton, the abrupt onset contained the same color as the background distractor color (see Figure 1, Panel A). The onset appeared equally often in the same side as the relevant color singleton cue as in the opposite side (10% of the trials each). As with the relevant color singleton cue, the abrupt onset did not reliably predict the target location

(25% valid vs. 75% invalid).

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 red (RGB values: 255, 0, 0; CIE [Yxy]: 21.3, 0.64, 0.33), one was green (RGB values of 0, 153, 0; CIE [Yxy]: 22.8, 0.30, 0.60), and the other two were white (RGB values of 255, 255, 255; CIE [Yxy]: 100, 0.31, 0.33). The two colored letters were always located in opposite hemifields.

Design and Procedure. As shown in Figure 2, 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 and back on for 1,200 ms to 1,400 ms (determined randomly with a uniform distribution). The cue display then appeared for 50 ms before being replaced by the fixation display for 100 ms. The target display then appeared for 50 ms. Thus, the interval between the onset of the cue display and the onset of the target display was 150 ms. The participants' task was to indicate whether the letter in the target color was a T or L. Specifically, participants were to press the leftmost response-box button with their left-index finger for the letter "L" and the rightmost button with their right-index finger for the letter "T". Feedback (a tone for an incorrect response or the fixation display for a correct response) was presented for 100 ms. The next trial then began with the 1,200-ms fixation display.

Participants performed one practice block of 30 trials, followed by 16 experimental blocks of 80 trials each (a total of 1,280 experimental trials). Eighty percent of the trials (1024 trials in total) contained only the relevant color singleton cue, whereas 20% of the trials (256 trials in total) contained both the relevant color singleton cue and the irrelevant abrupt onset.

The locations of the relevant color singleton cue and the target were randomly

determined, with each location being equally probable. Thus, the location of the relevant color singleton cue was the same as the location of the target for 25% of the trials (the valid condition), and different for 75% of the trials (the invalid condition). Thus, the cue location did not predict the target location. The same was true for the irrelevant abrupt onset. Note that we examined the cue validity effect and N2pc effect to the relevant color singleton cue as a function of whether the abrupt onset was present vs. absent. Although the validity distinction is critical in the behavioral analyses to measure the cue validity effect, it is not critical for measuring the N2pc effect to the relevant color singleton cue location. The N2pc effect in response to the relevant color singleton cue can be assessed both for valid and invalid trials. The distinction crucial to the N2pc analyses is whether the relevant color singleton cue and target are in the same hemifield or different hemifields (50% of trials in which the cue was present for each condition).

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 cue onset and ending 800 ms after cue onset. Each of these candidate artifact trials were then

inspected manually. Second, we computed average HEOG waveforms for the left-target and right-target trials, separately, to determine for each participant whether the eyes tended to move. Following Woodman and Luck (2003), we included in the data analyses only participants whose average HEOG activity was less than ± 3μV during the critical time windows (170-270 ms and 350-450 ms after cue onset). Three of the original 19 participants were eliminated because of artifact rejection on more than 25% of trials. Figure 3 shows the scalp topography of the grand average ERPs for the relevant color singleton cue trials (80% of trials).

The critical question in our study is whether the salient abrupt onset would capture attention and reduce or even eliminate the capture by the relevant color singleton cue. The N2pc data were analyzed as a function of whether the abrupt onset was absent (80% of the trials) or present (20% of the trials) and electrode site (P5/P6, O1/O2, and PO5/PO6 electrodes). To quantify the overall magnitude of the N2pc effect, we focused on the time window in which the irrelevant color singleton cue should produce an N2pc (170-270 ms after cue onset). The N2pc effect (i.e., the difference waveform) was measured as the mean amplitude during this time window for the electrode site contralateral to the *cue location* (e.g., the PO5 electrode when the cue was in the right hemifield) minus the mean amplitude for the electrode site ipsilateral to the *cue location* (e.g., the PO6 electrode when the cue was in the right hemifield), relative to the mean amplitude during a 200 ms pre-cue baseline period.

Although our experimental logic relies on the cue-elicited N2pc effect, we also reported the target-elicited N2pc effect. In the target-elicited N2pc data analyses, we focused on the time window in which the target should produce an N2pc effect (350-450 ms after cue onset, which translates to 200-300 ms after target onset).[1] To ensure consistency between the data analyses and presentation of the data (i.e., Figure 4, which plots the N2pc effect with respect to cue

location), we analyzed the target-elicited N2pc effect with respect to the cue location (rather than the location of the target itself). We submitted the mean amplitude of the difference waveforms (the N2pc effect) during the critical time windows to an analysis of variance (ANOVA), including same/different hemifield as an independent variable.

Results

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 2,000 ms (0.10% of trials). Rejection of trials with EEG artifacts led to the further elimination of 7% of trials, with no more than 18% rejected for any individual participant. Trials were also excluded from the RT and ERP analyses if the response was incorrect. An alpha level of .05 was used to ascertain statistical significance. Whenever appropriate, *p*-values were adjusted using the Greenhouse-Geisser epsilon correction for nonsphericity.

Behavioral Data Analyses

Although our experimental logic relies primarily on electrophysiological measures (reported below), we also looked for converging evidence in the behavioral data. Specifically, capture to the relevant color singleton cue location should result in smaller RT and/or lower PE when the upcoming target appeared in the same location as the relevant color singleton cue (valid trials) than when it did not (invalid trials). Thus, we assessed the cue validity effect elicited by a relevant color singleton cue with and without a simultaneous abrupt onset. Therefore, cue validity was defined as the relationship between the location of the relevant color singleton cue and the target. The behavioral data were analyzed as a function of group (red vs. green; a between-subject variable), validity of the relevant color singleton cue (valid vs. invalid), and cue condition (relevant cue only vs. relevant cue plus abrupt onset cue). Table 1 shows the

mean RT and PE for each of these conditions, averaged across groups.

For the RT data, a significant cue validity effect of 60 ms was obtained, $F(1, 14) = 160.92$, $p < .0001$, $\eta^2_p = .92$; RT was 572 ms for invalid trials and 513 ms for valid trials. RT was also 14 ms longer for the relevant-plus-onset cue (549 ms) than for the relevant cue only (535 ms), $F(1, 14) = 22.28$, $p < .001$, $\eta^2_p = .61$. The cue validity effect for the relevant color cue was larger when the abrupt onset was present (70 ms) than when it was absent (49 ms), $F(1, 14) = 11.97$, $p < .01$, $\eta^2_p = .46$. If anything, the onset actually increased capture by the relevant color cue, rather than competing with it (we will return to this unexpected finding in the General Discussion). No effect involving group was significant.

For the PE data, the cue validity effect of .023 was significant, $F(1, 14) = 11.16$, $p < .01$, $\eta^2_p = .44$; PE was .019 for valid trials and was .042 for invalid trials. Consistent with the RT data, the cue validity effect on PE for the relevant color cue was larger with the abrupt onset (.030) than without (.016), $F(1, 14) = 10.63$, $p < .01$, $\eta^2_p = .43$. No other effect was significant.

ERP Data Analyses

The N2pc effect (i.e., the average of the difference waveform) was measured from electrode sites relative to the relevant color singleton cue location. The N2pc effects were analyzed as a function of group (red vs. green; a between-subject variable), cue condition (relevant cue only vs. relevant cue plus abrupt onset cue), relevant cue/target spatial relationship (same hemifield vs. different hemifields), and electrode site (P5/P6, O1/O2, vs. PO5/PO6). We analyzed the average value of the difference waveform over two different time windows: 170-270 ms after cue onset (to assess the cue-elicited N2pc effect) and 350-450 ms after cue onset (to assess the target-elicited N2pc effect). Each of the subconditions contained 112 trials on average per participant after rejecting trials that were incorrect, fell outside our RT cutoff, or showed

ocular artifacts. Figure 4 shows the N2pc effect for the P5/P6, O1/O2, PO5/PO6 electrode sites, as well as the pooled data from these electrode sites, for the relevant cue only condition and the relevant cue plus abrupt onset cue condition, averaged across the two groups.

Cue-Elicited N2pc Effects. Our primary aim was to determine whether the rare abrupt onset captured attention, pulling it away from the relevant color singleton cue; if so, this would reduce the N2pc effect for the relevant cue. However, the main effect of cue condition was not significant, $F < 1.0$; the N2pc effect was -0.448 μV for the relevant cue only and was -0.382 μV for the relevant plus abrupt onset cue. The slight numerical decrease in the N2pc effect for the relevant plus abrupt onset cue was not significant and did not replicate in Experiment 2 (see below). Further *t*-tests revealed that both N2pc effects were significantly different from zero, $|ts(15)| \geq 2.97$, $ps \leq .01$. The N2pc effect was larger at the PO5/PO6 and P5/P6 electrode sites (-0.524 μV and -0.493 μV, respectively) than at the O1/O2 electrode site (-0.228 μV), $F(2, 28) = 10.32$, $p < .001$, $\eta^2_p = .42$. No other effects were significant.

Target-Elicited N2pc Effects. The target-elicited N2pc data (350-450 ms after cue onset) do not allow a test of our main hypothesis, but are included for the sake of completeness. Also note that, because we defined the N2pc effect with respect to the cue location (for consistency with the N2pc figures), the direction of the target-elicited N2pc effect should depend critically on whether the cue and target appeared in the same or different hemifield (see also Lien et al., 2010; Lien et al., 2008).

As predicted from the assumption that the target would capture attention, the target-elicited N2pc effect was negative when the target was in the same hemifield as the relevant cue (-0.516 μV) but was positive when the target was in the opposite hemifield (1.480 μV), $F(1, 14) = 36.78$, $p < .001$, $\eta^2_p = .72$.[2] This difference was more pronounced for the green target group (-

0.957 μV vs. 1.946 μV for same vs. different hemifields, respectively) than for the red target group (-0.074 μV vs. 1.013 μV), $F(1, 14) = 7.63$, $p < .05$, $\eta^2_p = .35$. The overall N2pc effect was more positive for the PO5/PO6 and P5/P6 electrode sites (0.669 μV vs. 0.513 μV, respectively) than for the O1/O2 electrode site (0.264 μV), $F(2, 28) = 10.13$, $p < .001$, $\eta^2_p = .42$. Finally, the interaction between electrode site and relevant cue/target spatial relationship was significant, $F(2, 28) = 13.68$, $p < .001$, $\eta^2_p = .49$. When the target and the relevant cue were in the same hemifield, the target-elicited N2pc effect was similar across the three electrode sites (-0.506 μV, -0.348 μV, and -0.692 μV for the PO5/PO6, O1/O2, and P5/P6 electrode sites, respectively). When they were in different hemifields, the N2pc effect was more positive for the PO5/PO6 and P5/P6 electrode sites (1.844 μV and 1.719 μV, respectively) than for the O1/O2 electrode site (0.876 μV). No other effects were significant.

Discussion

Experiment 1 examined whether a salient, but irrelevant abrupt onset can capture attention when it appears rarely. We adopted a cuing paradigm and pitted the abrupt onset cue against a simultaneous relevant color cue (see Lien et al., 2008). While 80% of the trials contained the relevant color singleton cue only, the remaining 20% of the trials contained both the relevant cue and an abrupt onset cue. If the abrupt onset has a strong pull on attention, it should reduce the ability of a relevant cue to capture attention. Both behavioral and ERP data, however, showed that this was not the case. The cue validity effect on RT for the relevant color singleton cue was not diminished by the presence of the abrupt onset (70 ms with abrupt onsets and 49 ms without abrupt onsets). If anything, the appearance of an abrupt onset in one location enhanced the capture by the relevant color singleton cue in a different location. Furthermore, the abrupt onset cue did not produce a cue validity effect; after excluding trials in which the relevant

color cue was valid, mean RT was actually longer for valid trials (602 ms) than invalid trials (567 ms), $t(15) = -4.07$, $p < .001$. Most important, the N2pc effect elicited by the relevant color cue was not eliminated or even significantly reduced by the presence of the abrupt onset, suggesting that even a rare onset has little pull on attention. There seems to be a small negative voltage within the time window 70-150 ms after cue onset in the relevant cue plus abrupt onset cue condition. If taken at face value, it would indicate a shift towards the relevant color cue (not towards the onset). We will come back to this issue in Discussion of Experiment 2.

## Experiment 2

There were two main purposes of Experiment 2. First, to provide an even more sensitive test of capture by rare abrupt onsets, we further reduced their frequency from 20% of trials in Experiment 1 to only 10% in Experiment 2. Second, we examined one possible explanation for the absence of capture by abrupt onsets in Experiment 1. The relevant color singleton cue appeared on 100% of the trials, and the abrupt onset appeared along with it on 20% of the trials. It is conceivable that inhibition of salient events depends not on how often a specific kind of salient distracting event (e.g., abrupt onsets) occurs, but how often any salient event occurs (e.g., onsets and/or relevant color singletons). In other words, the high proportion of trials with the relevant color singleton cue by itself could have weakened capture by the rare abrupt onset. Experiment 2 therefore reduced the proportion of trials with a relevant color cue alone from 80% of trials down to only 10%.

### Method

Participants. There were 26 new participants, drawn from the same participant pool as in Experiment 1. Again, none of them were in previous experiments. Four participants' data were excluded because either their averaged HEOG was larger than ± 3μV during the critical time

windows (170-270 ms and 350-450 ms after the cue onset) or their EEG artifact rejection was more than 25% of trials. Therefore, data from 22 participants (12 participants responded to the red letter and 10 to the green letter) were included in the final data analyses. All reported having normal or corrected-to-normal acuity. They also demonstrated normal color vision using the Ishihara Test for color deficiency.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except for the following change. Both the relevant color singleton cue condition and the relevant cue plus abrupt onset cue condition each comprised only 10% of the trials. As in Experiment 1, the onset appeared equally often in the same side as the relevant color singleton cue as in the opposite side (5% of trials each; see Figure 1, Panel B). The remaining 80% of trials contained no cue.

## Results

The data analysis was similar to that of Experiment 1. Application of the RT cutoffs eliminated 0.27% of the trials. Rejection of trials with EEG artifacts led to the further elimination of 3.64% of trials, but no more than 15% for any individual participant.

### Behavioral Data Analyses

The behavioral data were analyzed as a function of group (red vs. green; a between-subject variable), cue validity with respect to the relevant color singleton cue (valid vs. invalid) and cue condition (relevant cue only vs. relevant cue plus abrupt onset cue). Table 2 shows the mean RT and PE for each of these conditions, including the no cue condition, averaged across the two groups.

The RT data closely replicated those of Experiment 1. A significant cue validity effect of 56 ms was obtained, $F(1, 20) = 67.72$, $p < .0001$, $\eta^2_p = .77$; RT was 595 ms for invalid trials and

539 ms for valid trials. RT was also 22 ms longer for the relevant cue plus abrupt onset cue (578 ms) than for the relevant cue only (556 ms), $F(1, 20) = 9.77$, $p < .01$, $\eta^2_p = .33$. The cue validity effect for the relevant color cue was again larger when the abrupt onset was present (66 ms) than when it was absent (46 ms), $F(1, 20) = 14.59$, $p < .01$, $\eta^2_p = .42$, indicating that the abrupt onset did not pull attention away from the relevant cue (if anything, it did the opposite).

For PE data, the cue validity effect of .025 was significant, $F(1, 20) = 17.56$, $p < .001$, $\eta^2_p = .47$; PE was .039 for valid trials and was .064 for invalid trials. No other effects were significant.

ERP Data Analyses

The N2pc effect was measured from electrode sites relative to the relevant color singleton cue location. The N2pc data were analyzed as a function of group (red vs. green), cue condition (relevant cue only vs. relevant cue plus abrupt onset cue), relevant cue/target spatial relationship (same hemifield vs. different hemifields), and electrode site (P5/P6, O1/O2, vs. PO5/PO6). As in Experiment 1, we focused on two time windows: 170-270 ms after singleton cue onset (to assess the cue-elicited N2pc effect) and 350-450 ms after singleton cue onset (to assess the target-elicited N2pc effect). Figure 5 shows the N2pc effect for the P5/P6, O1/O2, PO5/PO6 electrode sites, as well as the pooled data from these electrode sites, for the relevant cue only and the relevant cue plus abrupt onset cue conditions, averaged across the two groups.

Cue-Elicited N2pc Effects. Our primary aim was to determine whether the rare abrupt onset would capture attention and thereby pull attention away from the relevant color singleton cue, reducing the N2pc effect for the relevant cue. No effects were significant. In particular, the critical main effect of cue condition was not significant, $F < 1.0$; the N2pc effect was -0.420 μV for the relevant cue only and was -0.490 μV for the relevant cue plus abrupt onset cue. Thus, the

abrupt onset had no apparent pull on spatial attention. Further *t*-tests revealed that both N2pc effects were significantly different from zero, $|ts(21)| \geq 4.34$, $ps \leq .001$, indicating (as expected) that the relevant cue by itself did capture attention.

Target-Elicited N2pc Effects. The target-elicited N2pc effect analyses (350-450 ms after cue onset) revealed that the target-elicited N2pc effect was negative when the target was in the same hemifield as the relevant cue (-0.437 μV) but was positive when the target was in the opposite hemifield (1.143 μV), $F(1, 20) = 43.64$, $p < .001$, $\eta^2_p = .69$. The overall target-elicited N2pc effect was more positive for the relevant cue only (0.600 μV) than for the relevant cue plus abrupt onset cue (0.105 μV), $F(1, 20) = 4.56$, $p < .05$, $\eta^2_p = .10$. Finally, the overall N2pc effect was more positive for the PO5/PO6 and P5/P6 electrode sites (0.669 μV and 0.513 μV, respectively) than for the O1/O2 electrode site (0.264 μV), $F(2, 30) = 10.58$, $p < .001$, $\eta^2_p = .41$. No other effects were significant.

Discussion

Experiment 2 further reduced the frequency of abrupt onset cues from 20% in Experiment 1 down to only 10%. We also reduced the frequency of relevant cue only trials from 80% in Experiment 1 to only 10% in Experiment 2. Thus, cues were much more rare, further reducing any incentive to actively inhibit them. Replicating the findings of Experiment 1, the N2pc effect elicited by the relevant color cue was not eliminated or even significantly reduced by the presence of the abrupt onset. Thus, even when the salient abrupt onset appeared on only 10% of trials (even smaller than the 18.75% frequency in Neo & Chua, 2006, which showed capture by abrupt onsets), there was no evidence that it could pull attention away from the relevant cue. The behavioral data were consistent with the N2pc results; the cue validity effect from the relevant color singleton cue on RT was not diminished by the presence of the abrupt onset (66

ms with abrupt onsets and 46 ms without abrupt onsets). If anything, the appearance of an abrupt onset in one location enhanced the capture by the relevant color cue in a different location. As in Experiment 1, the abrupt onset cue did not produce a cue validity effect; after excluding trials in which the relevant color cue was valid, mean RT was actually 26 ms slower for valid trials (623 ms) than invalid trials (597 ms), $t(21) = -2.64$, $p < .05$.

In both Experiments 1 and 2, there was a small negative voltage within the time window of 70 ms to 150 ms after cue onset in the relevant cue plus abrupt onset cue condition (Figures 4 and 5). It is important to note that this component cannot be considered as evidence for capture by salient abrupt onsets, for two reasons. First, the time course was too early to be considered as "attentional" in nature (in previous studies, the N2pc effect never begins at 70 ms). Second, the contralateral versus ipsilateral electrode sites used to calculate the N2pc effect elicited by the relevant color cue were based on the location of the relevant color cue, not the abrupt onset. Thus, even if the effect were attentional, it would reflect attention to the relevant color cue, not attention to the abrupt onset. The salient abrupt onset was located in the same hemifield as the relevant color singleton cue (but in different locations) for half of the trials and was in different hemifields for the other half. Thus, if the salient abrupt onset captured attention, one should expect an overall reduction in the N2pc effect elicited by the relevant color singleton cue, which was not what we observed.

## Experiment 3

Experiment 3 examined whether a different type of salient object, namely, an irrelevant color singleton has the power to capture spatial attention when it appears rarely. The cue display contained a salient-but-irrelevant color singleton amid several homogeneously-colored background items (e.g., a red box among several green boxes) on 20% of the trials. For the

remaining 80% of the trials, the cue display was neutral (all white boxes, unchanged from the fixation display). The colors used for the salient-but-irrelevant color singleton cue and the background boxes were never used in the target display, reducing the incentive to actively inhibit them.

As in Experiments 1 and 2, the target display always contained two colored letters and two white letters. Each participant looked for only one specific target color. Thus, the use of a specific top-down attentional setting (e.g., searching for a specific color) was necessary to perform the task, discouraging use of singleton-detection mode (e.g., Lien et al., 2008).

Method

Participants. There were 29 new participants, drawn from the same participant pool as in Experiment 1. None participated in the previous experiments. Five participants' data were excluded because their EEG artifact rejection rate was more than 25% of trials (see below), and one participant's EEG data failed to record. The remaining 24 participants (17 females and 7 males) had a mean age of 21 years (range: 18-28). Seven responded to the red letter, six to the green letter, six to the blue letter and the remaining five to the yellow letter. All reported having normal or corrected-to-normal acuity. They also demonstrated normal color vision using the Ishihara Test for color deficiency.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 2, except for the following changes. In addition to the red and green colors used in Experiment 2, we also used blue (RGB values of 0, 51, 255; CIE [Yxy]: 9.59, 0.15, 0.08) and yellow (RGB values of 255, 255, 0; CIE [Yxy]: 92.8, 0.42, 0.51). For 80% of the trials, the cue display was the same as the fixation display. For the remaining 20% of the trials, the four peripheral boxes in the cue display changed color, leaving one color singleton and three

identical-colored background boxes (e.g., one blue box and three yellow boxes). The center box also contained the background color. The assignment of specific colors (e.g., blue or yellow when the target was red or green) to the irrelevant color singleton cue and background in the cue display was randomly determined within blocks (10% of trials for one assignment and 10% for the other) for each participant.

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". For half of the participants, one letter was red, one was green, and the other two were white. For these participants, the colors blue and yellow were used in the cue display for the irrelevant color singleton box and the background boxes. For the other half of the participants, the assignment of red/green and blue/yellow was reversed. Thus, target display contained one blue letter, one yellow letter, and two white letters. The colors red and green were used in the cue display for the irrelevant color singleton box and the background boxes.

Results

The data analysis was similar to that of Experiments 1 and 2. Application of RT cutoffs eliminated 0.25% of trials. Rejection of trials with EEG artifacts led to the further elimination of 8% of trials, with no more than 25% rejected for any individual participant.

Behavioral Data Analyses

The behavioral data were analyzed as a function of group (red, green, blue, vs. yellow; a between-subject variable), and cue condition (no cue, valid cue, vs. invalid cue; a within-subject variable). Table 3 shows the mean RT and PE for each of these cue conditions, averaged across the four groups.[3]

RT did not vary across cue conditions, $F(2, 40) = 1.52$, $p = .23$, $\eta^2_p = .07$; mean RT was 555, 548, and 552 ms for no cue, valid cue, and invalid cue, respectively. Further *t*-tests revealed that the cue validity effect (4±9 ms) was not significantly different from zero, $t(23) = 1.05$, $p = .31$. As in the RT data, the PE data showed no effect of cue condition, $F(2, 40) = 1.03$, $p = .36$, $\eta^2_p = .05$ (PEs = .044, .042, and .051 for no cue, valid cue, and invalid cue, respectively). Further *t*-tests revealed that the cue validity effect on PE (.008±.017) was not significant, $t(23) = 1.03$, $p = .31$. The interaction between group and cue condition was significant on PE, $F(6, 40) = 2.45$, $p = .04$, $\eta^2_p = .27$. For the red target group, PE was lower (.019) for the valid cue than the invalid (.050) and no cue (.048) conditions. However, the pattern was opposite for the blue target group (PEs = .084, .067, and .057, for valid, invalid, and no cue, respectively). For the green and yellow target groups, PE was similar across all three cue conditions. No other effects were significant.

ERP Data Analyses

The N2pc effect (i.e., the average difference waveform) was measured from electrode sites relative to the irrelevant color singleton cue location. The N2pc effects were analyzed as a function of group (red, green, blue, vs. yellow; a between-subject variable), cue/target spatial relationship (same hemifield vs. different hemifields), and electrode site (P5/P6, O1/O2, vs. PO5/PO6). As in Experiments 1 and 2, we focused on two time windows: 170-270 ms after cue onset (to assess the cue-elicited N2pc effect) and 350-450 ms after cue onset (to assess the target-elicited N2pc effect). Figure 6 shows the N2pc effect for the P5/P6, O1/O2, PO5/PO6 electrode sites, as well as the pooled data from these electrode sites, averaged across the groups.

Cue-Elicited N2pc Effects. The cue-elicited N2pc analyses (170-270 ms after cue onset) revealed no significant main effects or interactions, $F$s $\leq 1.44$, $p$s $\geq .2503$, $\eta^2_p$s $\leq .16$; the N2pc

effect was 0.117 μV for the same hemifield and was 0.113 μV for the different hemifield trials. Thus, the irrelevant color singleton cue failed to produce an overall N2pc effect and the effect was not modulated by group or electrode site.

Target-Elicited N2pc Effects. The target-elicited N2pc analyses (350-450 ms after cue onset) revealed that the target-elicited N2pc effect was negative when the target was in the same hemifield as the singleton cue (-0.975 μV) but was positive when the target was in the opposite hemifield (1.304 μV), $F(1, 20) = 53.74$, $p < .0001$, $\eta^2_p = .73$.[4] This pattern was more pronounced for the P5/P6 and PO5/PO6 electrode sites than the O1/O2 electrode site, $F(2, 40) = 9.18$, $p < .001$, $\eta^2_p = .31$. No other effects were significant.

Discussion

Experiment 3 examined whether an irrelevant color singleton can capture attention when it appears rarely. The cue display contained an irrelevant color singleton cue on only 20% of the trials (the other 80% contained no cue, though the display timing was yoked to that of the cue present trials). The critical finding is that the irrelevant color singleton cue failed to produce an N2pc effect. The behavioral data are consistent with the N2pc data, showing a negligible and non-significant cue validity effect on RT (4±9 ms). Taken together, both the behavioral and electrophysiological findings are consistent with the claim that irrelevant color singletons do not elicit attentional capture even when they appear rarely.

## Experiments 4a and 4b

Relevant color singleton cues produced large cue validity and N2pc effects in Experiments 1 and 2, consistent with the contingent capture view. When essentially the same stimulus did not have the relevant color, but was still a color singleton, it appeared to be completely ignored (Experiment 3). This comparison suggests that relevance dominates

salience. Nevertheless, it is reasonable to ask whether the color singleton could capture attention if it were made much more salient. For instance, Theeuwes (2004) found that increasing display size enabling color singletons to capture attention (but see Lien et al.'s, 2010, ERP data). Experiment 4 therefore examined this possibility by replicating Experiment 3 but increasing the cue duration to 150 ms and the display size to 8 peripheral boxes.

We also modified the colors to further increase salience. First, we modified all the colors so that they would be more equiluminant and there would be less luminance change in the cue display to mask the color change. Also, we used only green and red as color singletons, against red or green background boxes in the cue display, because they have higher color contrast. We used blue and yellow colors in the target display.

A final change was that we manipulated singleton frequency (20% of trials in Experiment 4a vs. 100% in Experiment 4b), so we could directly assess the impact of rarity, apart from any effect of increased salience. These conditions were run between-subjects, so that there would be no carryover effect from one condition to the other.

Method

Participants. There were 20 new participants in Experiment 4a and 21 in Experiment 4b, drawn from the same participant pool as in Experiment 1. None participated in the previous experiments. Three participants' data were excluded because two participant's EEG artifact rejection rate was more than 25% of trials (one from each experiment), and one participant in Experiment 4b had accuracy lower than 80%. The remaining 19 participants (12 females) in Experiment 4a had a mean age of 21 years (range: 18-28), whereas the remaining 19 participants (11 females) in Experiment 4b had a mean age of 20 years (range: 18-23). Ten responded to the blue letter and the remaining 9 to the yellow letter in each experiment. All reported normal or

corrected-to-normal acuity. They also demonstrated normal color vision using the Ishihara Test for color deficiency.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 3, except for the following changes. First, we used approximately equiluminant colors: Red (RGB values of 255, 0, 0; CIE [Yxy]: 21.26, 0.64, 0.33), Green (RGB values of 0, 151, 0; CIE [Yxy]: 22.13, 0.30, 0.60), Blue (RGB values of 0, 128, 255; CIE [Yxy]: 22.66, 0.18, 0.16), and yellow (RGB values of 130, 130, 0; CIE [Yxy]: 20.71, 0.42, 0.51). Second, only red and green were used in the cue display and only blue and yellow were used for the target color (randomly assigned to each participant). The color singleton cue was either a red color singleton box amongst several green background boxes, or a green color singleton box amongst several red background boxes (randomly intermixed within a block). Third, we added four peripheral boxes arranged directly above, below, left, and right of the center box (see Figure 1, Panel D). They were the same size as the original four peripheral boxes and the same distance from the center box. The original four peripheral boxes remained in the same locations as in Experiment 3; participants were not informed that only these four locations could have contained the irrelevant color singleton cue and the target (both irrelevant color singleton cues and targets have never appeared inside the new boxes). An advantage of this approach is that the cue remained 25% valid and 75% invalid, as in Experiment 3. Fourth, the irrelevant color singleton cue was presented on 20% of the trials in Experiment 4a and 100% of the trials in Experiment 4b. Fifth, we increased the cue display duration from 50 ms to 150 ms while leaving the durations of all other events the same as in Experiment 3.

Results

The data analysis was similar to that of Experiment 3. Application of RT cutoffs

eliminated 0.22% and 0.15% of trials in Experiments 4a and 4b, respectively. Rejection of trials with EEG artifacts led to the further elimination of 5% of trials in both experiments, with no more than 25% rejected for any individual participant.

Behavioral Data Analyses

The behavioral data were analyzed as a function of group (blue vs. yellow; a between-subject variable), and cue condition (no cue, valid cue, vs. invalid cue) in Experiment 4a, and a function of a function of group (blue vs. yellow), and cue condition (valid vs. invalid) in Experiment 4b.[5] Table 4 shows the mean RT and PE for each of the cue conditions in each experiment.

Experiment 4a (20% cue presence). For the RT data, the main effect of cue condition was significant, $F(2, 34) = 4.67$, $p < .05$, $\eta^2_p = .22$; mean RT was 586 ms, 580 ms, and 599 ms for no cue, valid cue, and invalid cue, respectively. Further analyses revealed that RT was significantly slower in the invalid cue condition than the valid and no cue conditions, $F$s$(1, 17) \geq 5.69$, $p$s $< .05$, $\eta^2_p$s $\geq .25$, but there was no difference between the latter two conditions, $F < 1.0$. Further *t*-tests revealed that the cue validity effect of 19±16 ms was significantly different from zero, $t(18) = 2.49$, $p < .05$. For the PE data, the main effect of group was significant, $F(1, 17) = 5.52$, $p < .05$, $\eta^2_p = .25$; the target blue group produced a smaller PE than the target yellow group (.050 vs. .092, respectively). No other effects were significant.

Experiment 4b (100% cue presence). For the RT data, the cue validity effect (8±11 ms) was small and non-significant, $F(1, 17) = 2.72$, $p = .12$, $\eta^2_p = .14$; mean RT was 588 and 596 ms for valid and invalid cues, respectively. The cue validity effect was larger for the target blue letter group (19±14 ms) than the target yellow letter group (-5±14 ms), $F(1, 17) = 7.69$, $p < .05$, $\eta^2_p = .31$. As in the RT data, the PE data showed no effect of cue validity, $F < 1.0$ (the effect

was only -.003±.009). No other effects were significant.

ERP Data Analyses

The N2pc effect was measured from electrode sites relative to the irrelevant color singleton cue location and analyzed as a function of group (blue vs. yellow; a between-subject variable), cue/target spatial relationship (same hemifield vs. different hemifields), and electrode site (P5/P6, O1/O2, vs. PO5/PO6) in each experiment. As in Experiments 1-3, the time window used to assess the cue-elicited N2pc effect was 170-270 ms after cue onset. However, due to the 100-ms increase in cue duration, the time window used to assess the target-elicited N2pc effect was 450-550 ms after cue onset (i.e., 200-300 ms after target onset). Figure 7 shows the N2pc effect for the P5/P6, O1/O2, PO5/PO6 electrode sites, as well as the pooled data from these electrode sites, averaged across groups, for each experiment.

Cue-Elicited N2pc Effects. In both Experiments 4a and 4b, the cue-elicited N2pc analyses (170-270 ms after cue onset) revealed no significant main effects or interactions, $F$s ≤ 2.77, $p$s ≥ .0843, $\eta^2_p$s ≤ .14. There seems to be a trend toward a reverse N2pc effect in Experiment 4a (the overall N2pc effect was 0.242 μV), $t(18) = 1.94$, $p = .0686$, whereas the overall N2pc effect was only -0.054 μV in Experiment 4b, $|t| < 1.0$. As in Experiment 3, the irrelevant color singleton cue did not produce N2pc effects during the time window 170-270 ms after cue onset.

Nevertheless, a close inspection of the ERP data revealed an N2pc effect in the early time window (170-210 ms). The overall N2pc effect in the early window was -0.318 μV and -0.418 μV in Experiments 4a and 4b, respectively, $|t$s$(18)| \geq 2.40$, $p$s $< .05$. The between-experiment comparison showed no statistical difference in the magnitude of N2pc effects, $t < 1.0$.

Target-Elicited N2pc Effects. For Experiment 4a (20% cue presence), the target-elicited

N2pc analyses (450-550 ms after cue onset) revealed that the target-elicited N2pc effect was negative when the target was in the same hemifield as the singleton cue (-0.307 μV) but was positive when the target was in the opposite hemifield (0.619 μV), $F(1, 17) = 18.31$, $p < .001$, $\eta^2_p = .52$.[6] This pattern was less pronounced for the target blue group (0.060 μV vs. 0.493 μV, respectively) than for the target yellow group (-0.715 μV vs. 0.758 μV, respectively), $F(1, 17) = 5.46$, $p < .05$, $\eta^2_p = .24$. No other effects were significant.

Similar results were obtained in Experiment 4b (100% cue presence). The target-elicited N2pc analyses (450-550 ms after cue onset) revealed that the target-elicited N2pc effect was negative when the target was in the same hemifield as the singleton cue (-0.872 μV) but was positive when the target was in the opposite hemifield (1.009 μV), $F(1, 17) = 30.60$, $p < .0001$, $\eta^2_p = .64$. This pattern was less pronounced for the target blue group (-0.391 μV vs. 0.784 μV, respectively) than for the target yellow group (-1.407 μV vs. 1.259 μV, respectively), $F(1, 17) = 4.61$, $p < .05$, $\eta^2_p = .21$. In addition, the difference between same and different hemifield conditions was more pronounced for the PO5/PO6 electrode site than the P5/P6 and O1/O2 electrode sites, $F(2, 34) = 12.06$, $p < .001$, $\eta^2_p = .41$, which was also more pronounced for the target yellow group than the target blue group, $F(2, 34) = 8.62$, $p < .001$, $\eta^2_p = .34$. No other effects were significant.

Discussion

Our primary aim in Experiment 4 was to determine whether increase the salience of the irrelevant color singleton cue would enhance the impact of rarity on attention capture. We therefore made four major changes to the design of Experiment 3 to increase color singleton salience: (1) we increased the number of background boxes, (2) we increased the cue duration, (3) we used only red and green cues (to achieve higher color contrast), and (4) we used more

equilumant colors so that luminance changes would not mask color changes. Finally, we presented the irrelevant color cue for 20% of the trials in Experiment 4a but 100% in Experiment 4b, to determine whether any capture observed is due to rarity or to increased salience.

With the increased salience of the irrelevant color singleton cue, we found a significant cue validity effect (19±16 ms) on RT in Experiment 4a, with 20% cue presence, and a small but nonsignificant cue validity effect (8±11 ms) in Experiment 4b, with 100% cue presence. Further *t*-test on the cue validity effect between Experiments 4a and 4b showed no significant effect of rarity, $t(36) = 1.23$, $p = .2260$. In addition, the cue validity effect in Experiment 4a was not significantly greater than it was in Experiment 3 (4±9 ms), at the same cue frequency, $t(41) = -1.65$, $p = .1096$.

Even though the ERP data showed no significant N2pc effect during the time window 170-270 ms after cue onset, there was an effect during the time window 170-210 ms, which was larger in Experiment 4a than Experiment 3 (-0.318 μV vs. -0.025 μV, respectively), $t(41) = 1.96$, $p = .0568$. Nevertheless, the N2pc effects were not significantly different between Experiments 4a and 4b (-0.318 μV and -0.418 μV, respectively), $t < 1.0$. Thus, although the increased salience appeared to increase capture (albeit relatively weak and short-lived), there was no more capture with rare stimuli than with the frequent stimuli. Taken together, both the behavioral and ERP findings suggest that rarity by itself is not necessary to elicit attentional capture.

## General Discussion

Several previous studies have reported cases where rarity increased capture (e.g., Neo & Chua, 2006), whereas others have reported that rare salient objects did not capture attention even when they were irrelevant to the current task set (e.g., Yantis & Egeth, 1999). Some of the confusion may stem from the indirectness of behavioral data (e.g., RT), which opens the door to

numerous alternative explanations. For example, people have argued that the RT costs of surprise might cancel out the benefits of capture, or that the shift occurred too early or too late to influence RT. The present study used a more specific and sensitive measure of capture (i.e., the N2pc effect) to determine whether rarity leads to capture by salient stimuli.

We used a cuing paradigm, in which a cue display appeared prior to the target display, to minimize ERP overlap between capture by the rare, salient cue and capture by the target. The cue was always uninformative regarding the target location (25% valid vs. 75% invalid). One important aspect of our design was that the target was always a non-singleton (e.g., the target display might include one red, one green, and two white letters), so that looking for a specific target feature was necessary to perform the task correctly. Capture by rare, salient objects with absolutely no target features would strongly support the claim that capture is driven by salience in a bottom-up manner. It would also implicate an important role of inhibition.

Experiment 1 examined capture by rare abrupt onsets. Specifically, we examined whether an abrupt onset could pull attention away from a cue drawn in the target-relevant color. The relevant color singleton cue (containing the target feature) appeared on 100% of the trials and the abrupt onset appeared simultaneously with the relevant color singleton cue (but in a different location) on only 20% of the trials. As expected, the relevant color singleton cue produced a significant N2pc effect, indicating that it captured attention. Most important, this N2pc effect was not abolished or even reduced by the simultaneous presence of the abrupt onset. The behavioral data were consistent with the N2pc effect. The cue validity effect produced by the relevant color singleton cue was 49 ms when it was presented alone and was 70 ms when it appeared simultaneously with the abrupt onset. Thus, there was no evidence that the abrupt onset, despite being rare, had any ability to pull attention away from a relevant color cue.

Experiment 2 further reduced the frequency of abrupt onsets from 20% to 10% and also reduced the frequency of the relevant color cue alone trials from 80% to 10%. Despite the large reduction in the frequency of salient cue events, we still replicated the results of Experiment 1. The N2pc effect elicited by the relevant color singleton cue was not reduced by the presence of the abrupt onset. The behavioral data converged on the same conclusion – the cue validity effect produced by the relevant color singleton cue was 46 ms when it was presented alone and was 66 ms when it appeared simultaneously with the abrupt onset.

One interesting and unexpected finding from Experiments 1-2 is that the cue validity effect produced by the relevant color singleton cue was larger when the abrupt onset was present (70 ms and 66 ms in Experiments 1 and 2, respectively) than when it was absent (49 ms vs. 46 ms). So the abrupt onset showed no ability to pull attention toward itself, but instead appeared to help the relevant cue capture attention (see also Lien, Ruthruff, & Gaspelin, submitted). The mere presence of the abrupt onset somewhere in the display, regardless of its precise location, might boost capture by a relevant stimulus. For instance, the salient abrupt onset might temporarily increase overall alertness, which in turn accelerates attentional shifts towards relevant objects.

Experiment 3 looked for capture by rare color singletons. An irrelevant color singleton cue (drawn in a color that never appeared in the target display) was presented on 20% of the trials. The remaining 80% of the trials contained no cue. Despite being rare, color singletons produced no N2pc effect. The behavioral data were consistent with this finding. RT was similar for the cue and no-cue conditions and there was no significant difference in RT between valid and invalid cue trials (i.e., no cue validity effect).

Experiment 4 greatly increased the salience of the irrelevant color singleton cue by

increasing the duration of the cue display from 50 ms to 150 ms and the number of background boxes from 4 to 8. Only red and green were used in color singleton display, because they have higher color contrast, and only blue and yellow as the target color. We also used more equiluminant colors so that the luminance changes would be less likely to mask color changes. The irrelevant color singleton cue appeared 20% of the trials in Experiment 4a and 100% of the trials in Experiment 4b. With greatly increased salience, we found a small capture effect in the behavioral data (cue validity effects were 19±16 ms vs. 8±11 ms in Experiments 4a and 4b, respectively, albeit nonsignificant in the latter). Nevertheless, the overall cue validity effect produced by the irrelevant color singleton cue (averaged across Experiments 4a and 4b) was only 29% of the overall cue validity effect produced by the relevant color singleton cue (averaged across Experiments 1 and 2). The cue-elicited N2pc data are also consistent with behavioral data, showing signs of short-lived, early capture (during the time window 170-210 ms after cue onset). Most important, the between-experiment comparison on the N2pc effect revealed no more capture with rare stimuli than with those salient, frequent stimuli. Together, the present findings (both N2pc effects and cue validity effects) suggest that capture by salient objects does not strongly depend on rarity.

Thus, rarity appears to be neither necessary nor sufficient to produce capture by salient objects. Some previous studies have revealed evidence for capture by irrelevant, salient objects even when they were presented very frequently (e.g., Jonides & Yantis, 1988; Remington, Johnston, & Yantis; 1992; Yantis & Jonides, 1984; to a small extent, the present Experiment 4b; but see also Lien et al., 2008). Moreover, rarity does not always lead to capture. Our salient events were rare in Experiments 1 and 3 (only 20% of trials), yet no capture by salient objects was observed (see also Horstmann & Ansorge, 2006; Yantis & Egeth, 1999). The absence of

capture was also evident even when we further reduced the frequency from 20% to only 10% in Experiment 2. Furthermore, color singletons produced no more capture when they were rare than when they were frequent (Experiment 4a vs. 4b). In sum, although rarity might play a role in some situations, it does not appear to generally be a critical determinant of capture.

Decrease in Capture Across Trials?

In the present study, the salient-but-irrelevant object (the abrupt onset and the irrelevant color singleton) appeared on only 10% to 20% of the trials (with the exception of Experiment 4b). Capture by these salient objects was assessed based on trial-averaged data rather than a single, critical trial, as in some previous studies of surprise capture (e.g., Gibson & Jiang, 1998; Godijn & Kramer, 2008; Horstmann, 2002; Horstmann & Becker, 2008). It is therefore conceivable that salient stimuli did capture attention the first few times it was presented, but then inhibition was eventually applied (even though inhibition would not be needed on the 80-90% of trials with no cue). Thus, averaging data across those trials may have resulting in an underestimation of initial capture by rare, salient objects. For instance, Godijn and Kramer (2008) examined oculomotor capture by surprising onsets on a trial-by-trial basis. Saccadic movement toward the abrupt onset occurred for 28% of the participants for the first occurrence of the onset, but for only 5% of the participants on subsequent presentations. As converging evidence of capture by surprising onsets, saccadic latencies to targets simultaneously presented somewhere else were longer for the first occurrence of the onset than for the subsequent occurrences. Godjin and Kramer concluded that the novelty of the onset modulates oculomotor capture. Although their findings seem compelling, there are other possible explanations for the reduction in occulomotor capture over time observed by Godjin and Kramer. For instance, participants might have developed a sharper representation of the target stimulus, allowing it to

be fixated more rapidly and with less error (i.e., fewer shifts to distracting stimuli).

Although it is not feasible to measure the N2pc for individual trials, it is possible to examine session halves. The capture by surprise hypothesis predicts that the strength of the capture effect by the rare object would be greatest for the first few encounters and then decrease over time. To critically evaluate this possibility, we examined the cue validity effect for the first half of the rare cue trials (i.e., the irrelevant abrupt onset trials) versus the second half of those cue trials on the pooled data from Experiments 1 and 2. The data analyses on the cue validity effect produced by the relevant color cue, with the variables of cue condition (with vs. without abrupt onsets) and session (first half vs. second half), revealed no significant validity by session interaction, $F < 1.0$. The non-significant trend went in the opposite direction (67±12 ms cue validity effect with abrupt onsets and 51±9 ms without abrupt onsets for the first half of the trials; 68±13 ms and 44±11 ms, respectively, for the second half). Consistent with the behavioral data, the cue-elicited N2pc effect analyses revealed no significant interaction between cue condition and session, $F < 1.0$. The N2pc effects by the relevant color cue with and without abrupt onsets were -0.315 μV and -0.352 μV, respectively, for the first half, and were -0.545 μV and -0.471 μV for the second half.

A similar analysis was conducted for the pooled data from Experiments 3 and 4a (both 20% cue presence), examining irrelevant color singletons rather than abrupt onsets. The data analysis on the cue validity effect with the variable of session (first half vs. second half) revealed no sign of a decreasing cue validity effect from the first half of the session to the second half, $t < 1.0$ (the effect was 11±5 ms for the first half and was 9±6 ms for the second half). Consistent with the behavioral data, the cue-elicited N2pc effect analyses for the time window 170-270 ms after cue onset also revealed no effect of session half, $t < 1.0$ (the N2pc effect was actually

reversed: 0.208 μV and 0.139 μV for the first and second half of the trials, respectively). Even with the analysis focusing on the time window 170-210 ms after cue onset in Experiment 4a, there was still no session effect, $t < 1.0$; in fact, the N2pc effect was numerically larger for the second half session (-0.374 μV) than the first half (-0.205 μV). In summary, we found no evidence for the claim that rare abrupt onsets or rare irrelevant color singletons captured attention early in the session but not late in the session.

Relations to Other Studies

The critical finding of the present electrophysiological study is that rarity does not appear to generally be a critical determinant of capture. Töllner, Müller, and Zehetleitner (2012) recently examined capture with different probabilities of irrelevant color singleton distractors and how capture was modulated by inter-trial priming. They used a visual search paradigm, in which participants looked for a line tilted $\pm 15^0$ among 8, 12, or 18 background vertical lines. All lines contained a gap at the top or bottom and participants had to determine the gap location of the target line. All lines, including the tilted target line, were presented in the same color. However, an additional irrelevant color singleton distractor appeared on 25% or 50% of the trials. They measured Posterior-Contralateral-Negativity (PCN; similar to the N2pc effect). They found that the irrelevant color singleton distractor failed to elicit a PCN, suggesting that it did not capture attention. Nevertheless, the target-elicited PCN was modulated by the probability of the irrelevant color singleton distractor and the inter-trial relationship. Specifically, the target-elicited PCN was delayed for the low probability condition and when there was no distractor presented on the preceding trial. As discussed above, the sudden appearance of the discrepant stimulus might interrupt the current goal-driven behavior, requiring reestablishment of the top-down task set and thereby delaying target processing (see Woods &

Patterson, 2001).

Even though we found that abrupt onsets did not pull attention away from a relevant cue in Experiments 1-2, the finding leaves open the logical possibility that the abrupt onset somehow managed to capture attention to itself while having no impact on capture by the relevant cue. It also remains possible that other types of salient stimuli might be able to capture attention only when rare or surprising or capture by salient object occurs in the absence of a strong top-down task set for specific target features. For instance, Becker and Horstmann (2011) found that a surprising, unexpected motion singleton (i.e., a rotating square) captured attention despite top-down control settings for a specific shape, using a design similar to Gibson and Jiang's (1998) single critical trial manipulation. An array of Landolt C's within squares was presented at either set size 4 or 8, one of which had a gap in the horizontal orientation. Participants determined whether this gap faced left or right. On the critical trial, the target location was always validly cued by a simultaneously-presented rotating square. Unlike Gibson and Jiang (1998), who found no evidence of capture by a surprising color singleton, Becker and Horstmann (2011) found evidence of capture by the rotating square. Specifically, there was no setsize effect on gap detection RT for the critical trial, indicating that visual attention was allocated first to the location of the novel motion singleton. This capture occurred only when the motion was an unexpected feature that participants had never encountered before.

Unlike color singletons and abrupt onsets, motion may have the inherit power to capture our attention involuntarily (see also Abrams & Christ, 2003; Al-Aidroos, Guo, & Pratt, 2010; Pratt, Radulescu, Guo, & Abrams, 2010). From an evolutionary perspective, attention capture by moving objects is essential for survival. For instance, these moving objects might alert us to dangers within the environment or possible sources of food. Thus, the capture by rare, novel

moving objects may be a special case that reflects an involuntary bottom-up attention capture. This possibility deserves further investigation.

Another possibility is that capture by salient stimuli depends on the nature of the task being performed. For instance, Hickey et al. (2006) have provided evidence for capture by irrelevant color singletons when participants looked for a shape singleton (e.g., a diamond among circles). On 2/3 of the trials, one of the background, non-singleton shape object contained a unique color (the irrelevant color singleton; e.g., red among all green). They found that the irrelevant color singleton delayed responses for the target shape singleton. The target-elicited N2pc effect was smaller with the presence of the irrelevant color singleton than the absence of the irrelevant color singleton. These findings are generally consistent with the salience capture view. However, it has been argued that participants might have adopted a strategy of looking for any singleton object (known as singleton-detection mode; e.g., Bacon & Egeth, 1994).

Conclusions

Using both behavioral and electrophysiological measures, the present study investigated whether rarity is the critical ingredient for enabling capture by salient but irrelevant objects. Despite being salient and rare (appearing on 20% or even 10% of trials), abrupt onsets failed to capture attention away from a cue drawn in the target color. Similarly, irrelevant color singletons (appearing on 20% of trials) failed to produce the usual signs of attentional capture – cue validity effects and N2pc effects. Even when we made the color singleton much more salient (Experiment 4), rarity had no impact on capture. These findings support the claim that attention capture depends strongly on top-down control settings, not rarity. Rarity in the range examined here (10% and 20%) is neither necessary nor sufficient for attention capture.

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**Footnote**

1. The time window for the N2pc effect typically ranges from 150 to 300 ms after stimulus onset, but the exact timing depends somewhat on stimulus display and task demands (see Luck & Hillyard, 1994; Woodman & Luck, 2003). Our cue display and target display contained different objects, so one cannot assume identical N2pc time windows. Furthermore, the time course for the target-elicited N2pc also depends on preceding cue conditions. Thus, we used different time windows to assess the cue-elicited N2pc effect and the target-elicited N2pc effect, based on when the effect was strongest in the aggregate data.
2. The target-elicited N2pc effect analyses revealed a significant effect of cue/target spatial relationship (same hemifield vs. different hemifields) due to how we defined contralateral and ipsilateral ERPs in calculating the N2pc effect (i.e., with respect to the cue location). We repeated the analysis of target-elicited N2pc effect coded with respect to the target location, rather than cue location. Results showed that the main effect of cue/target spatial relationship was significant, $F(1, 14) = 34.34$, $p < .0001$, $\eta^2_p = .71$. A similar result was observed in Experiment 2, $F(1, 20) = 43.64$, $p < .0001$, $\eta^2_p = .39$. The observed pattern – a smaller target-elicited N2pc effect for the same hemifield than different hemifield conditions – was as expected. Given that attention has already been allocated to the relevant color cue, a target appearing in the same hemifield did not require as much of an attentional shift as a target appearing in the opposite hemifield.
3. We reported the mean RT and PEs for each cue condition averaged across groups in Table 3 for ease of readability. More detailed data, broken down by target color and irrelevant cue color, can be found at http://people.oregonstate.edu/~lienm/RarityCaptureSupplement.pdf
4. We repeated the analyses of target-elicited N2pc effects with respect to target location and

found that the main effect of cue/target spatial relationship was small and only marginally significant, $F(1, 20) = 3.95$, $p = .061$, $\eta^2_p = .16$. Note that because attention was not captured by the irrelevant color singleton cue, one would not expect attention allocation to the target (i.e., the target-elicited N2pc effect) to vary as a function of where the cue appeared in relation to the target.

5. We did not conduct an overall ANOVA including experiment (Experiments 4a vs. 4b) as a variable since the level of cue condition was different between these two experiments (only 4a has a no-cue condition). Nevertheless, a between-experiment comparison on cue validity effects was reported in the Discussion section of Experiment 4.
6. We repeated the analyses of target-elicited N2pc effects with respect to target location and found that the main effect of cue/target spatial relationship was not significant in both Experiments 4a and 4b, $F$s $< 1.56$, $p$s $\geq .2284$. The capture by the irrelevant color singleton cue occurred early during the time window 170-210 ms after cue onset. The increased duration between the cue onset and the target onset (250 ms) in Experiment 4 would allow attention to reallocate back to the central location prior to target onset. Therefore, one would not expect attention allocation to the target (i.e., the target-elicited N2pc effect) to vary as a function of where the irrelevant color singleton cue appeared in relation to the target location.

Table 1.

Mean Response Times (RT) in Milliseconds and Proportion of Errors (PE) as a Function of Cue Condition (Relevant vs. Relevant Plus Abrupt Onset) and Cue Validity with Respect to the Relevant Cue (Valid vs. Invalid) in Experiment 1. The Percentage of Trials Containing Each Cue Condition is Shown in Brackets.

| Cue Condition | Cue Validity | | *Cue validity effect* |
|---|---|---|---|
| | Valid | Invalid | |
| | RT | | |
| Relevant [80%] | 511 (16) | 560 (17) | *49 (5)* |
| Relevant + Abrupt Onset [20%] | 514 (16) | 585 (16) | *70 (7)* |
| | PE | | |
| Relevant [80%] | .021 (.004) | .037 (.010) | *.016 (.006)* |
| Relevant + Abrupt Onset [20%] | .016 (.005) | .046 (.011) | *.030 (.008)* |

*Note:* The standard error of the mean is shown in parentheses.

Table 2.

Mean Response Times (RT) in Milliseconds and Proportion of Errors (PE) as a Function of Cue Condition (Relevant, Relevant Plus Abrupt Onset, and No Cue) and Cue Validity with Respect to the Relevant Cue (Valid vs. Invalid) in Experiment 2. The Percentage of Trials Containing Each Cue Condition is Shown in Brackets.

| Cue Condition | Cue Validity | | *Cue validity effect* |
|---|---|---|---|
| | Valid | Invalid | |
| | RT | | |
| Relevant [10%] | 533 (24) | 579 (21) | *46 (7)* |
| Relevant + Abrupt Onset [10%] | 545 (27) | 611 (28) | *66 (7)* |
| No cue [80%] | 565 (22) | | |
| | PE | | |
| Relevant [10%] | .036 (.009) | .064 (.009) | *.028 (.007)* |
| Relevant + Abrupt Onset [10%] | .042 (.011) | .064 (.016) | *.022 (.010)* |
| No cue [80%] | .046 (.006) | | |

*Note:* The standard error of the mean is shown in parentheses.

Table 3.

Mean Response Times (RT) in Milliseconds and Proportion of Errors (PE) as a Function of Cue Condition (No Cue vs. Irrelevant Color Singleton) and Cue Validity (Valid vs. Invalid) in Experiment 3. The Percentage of Trials Containing Each Cue Condition is Shown in Brackets.

| | No Cue [80%] | Irrelevant Color Singleton [20%] | | *Cue Validity Effect* |
|---|---|---|---|---|
| | | Valid | Invalid | |
| RT | 555 (19) | 548 (18) | 552 (17) | *4 (4)* |
| PE | .044 (.007) | .042 (.009) | .051 (.008) | *.008 (.008)* |

*Note:* The standard error of the mean is shown in parentheses.

Table 4.

Mean Response Times (RT) in Milliseconds and Proportion of Errors (PE) as a Function of Cue Validity (Valid vs. Invalid) in Experiment 4a and Experiment 4b. The Percentage of Trials is Shown in Brackets.

| | No Cue [80%] | Irrelevant Color Singleton | | *Cue Validity Effect* |
|---|---|---|---|---|
| | | Valid | Invalid | |
| | | *Experiment 4a [20%]* | | |
| RT | 586 (17) | 580 (17) | 599 (19) | *19 (8)* |
| PE | .065 (.010) | .067 (.013) | .078 (.010) | *.012 (.010)* |
| | | *Experiment 4a [100%]* | | |
| RT | — | 588 (24) | 596 (23) | *8 (5)* |
| PE | — | .065 (.011) | .062 (.009) | *-.003 (.004)* |

*Note:* The standard error of the mean is shown in parentheses.

## Figure Captions

Figure 1. Example cue displays of Experiments 1-4 (Panels A-D). The target color was red in the example displays Panel A-C, whereas the target color was blue in the example display Panel D. Panel A: The boxes and the abrupt onset were green except the relevant color singleton cue noted in the displays. Panel B: The displays were similar to Panel A, except that the boxes were white in the no-cue condition. Panel C: The boxes were white except noted in the displays. Panel D: Only the red or green color singleton cues were used in the cue display. When the irrelevant color singleton cue was red, the background boxes were green. When the irrelevant color singleton cue was green, the background boxes were red. In Experiment 4a, the irrelevant color singleton cue appeared on only 20% of the trials, whereas the remaining 80% of the trials contained no cue (i.e., a homogenous display of red color boxes). The percentage of the trials was shown for each cue condition.

Figure 2. An example event sequence for the relevant color singleton cue with an abrupt onset condition in Experiment 1. In the real experiment, the boxes in the cue display and letters in the target display were colored. In this example, participants were instructed to respond to the red letter. In the cue display, the top-left box was red, while the other boxes were green. The abrupt onset was green. In the target display, the top-left letter "T" was red, the bottom-left letter "L" was white, the top-right letter "L" was green, and the bottom-right letter "T" was white.

Figure 3. Scalp topography of grand average event-related potentials for the relevant color singleton cue trials during the time window of 170-270 ms (left panel) and 350-450 ms (right panel) after cue onset in Experiment 1.

Figure 4. Grand average N2pc difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the relevant cue location from activity in electrode sites contralateral

to the relevant cue location at the P5/P6, O1/O2, and PO5/PO6 electrode sites in Experiment 1. In addition, pooled data were obtained by averaging the N2pc difference waveforms across all three electrode pairs. Data are plotted as a function of whether the cue and the target were in the same hemifield or different hemifields for the relevant cue only condition and the relevant cue plus onset cues condition. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 170-270 ms after cue onset (for the cue-elicited N2pc effect) and 350-450 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upward and time zero represents cue onset.

Figure 5. Grand average N2pc difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the relevant cue location from activity in electrode sites contralateral to the relevant cue location at the P5/P6, O1/O2, and PO5/PO6 electrode sites in Experiment 2. In addition, pooled data were obtained by averaging the N2pc difference waveforms across all three electrode pairs. Data are plotted as a function of whether the cue and the target were in the same hemifield or different hemifields for the relevant cue only condition and the relevant cue plus onset cues condition. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 170-270 ms after cue onset (for the cue-elicited N2pc effect) and 350-450 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upward and time zero represents cue onset.

Figure 6. Grand average N2pc difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the irrelevant color singleton cue location from activity in electrode sites contralateral to the color singleton cue location at the P5/P6, O1/O2, and PO5/PO6 electrode sites in Experiment 3. In addition, pooled data were obtained by averaging the N2pc difference waveforms across all three electrode pairs. Data are plotted as a function of whether

the cue and the target were in the same hemifield or different hemifields. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 170-270 ms after cue onset (for the cue-elicited N2pc effect) and 350-450 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upward and time zero represents cue onset.

Figure 7. Grand average N2pc difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the irrelevant color singleton cue location from activity in electrode sites contralateral to the color singleton cue location at the P5/P6, O1/O2, and PO5/PO6 electrode sites in Experiments 4a and 4b. In addition, pooled data were obtained by averaging the N2pc difference waveforms across all three electrode pairs in each experiment. Data are plotted as a function of whether the cue and the target were in the same hemifield or different hemifields. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 170-270 ms after cue onset (for the cue-elicited N2pc effect) and 450-550 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upward and time zero represents cue onset.

Figure 1

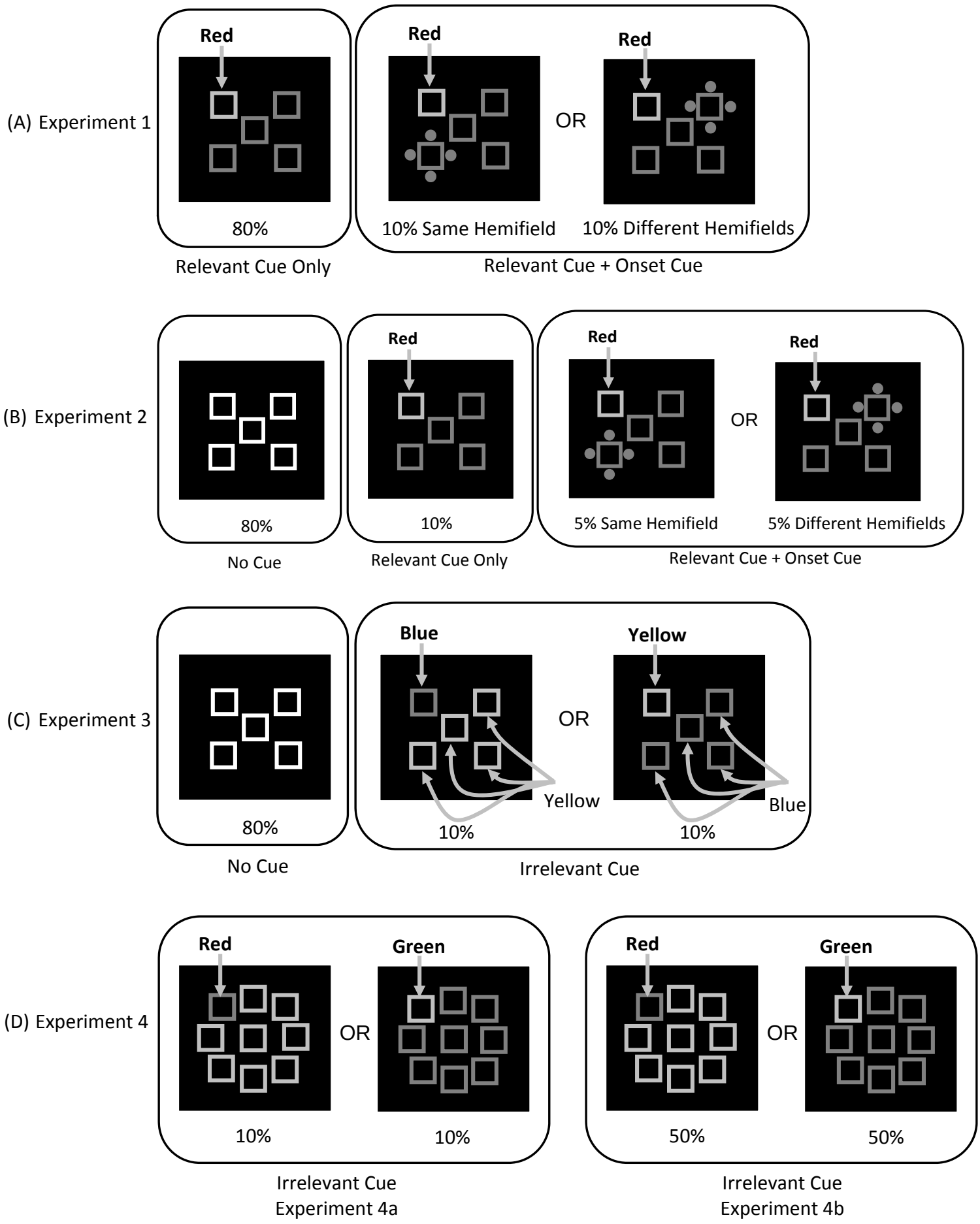

(A) Experiment 1
Red
80%
Relevant Cue Only
Red
10% Same Hemifield
OR
Red
10% Different Hemifields
Relevant Cue + Onset Cue
(B) Experiment 2
80%
No Cue
Red
10%
Relevant Cue Only
Red
5% Same Hemifield
OR
Red
5% Different Hemifields
Relevant Cue + Onset Cue
(C) Experiment 3
80%
No Cue
Blue
OR
Yellow
Yellow
Blue
10%
10%
Irrelevant Cue
(D) Experiment 4
Red
OR
Green
10%
10%
Irrelevant Cue
Experiment 4a
Red
OR
Green
50%
50%
Irrelevant Cue
Experiment 4b

Figure 2

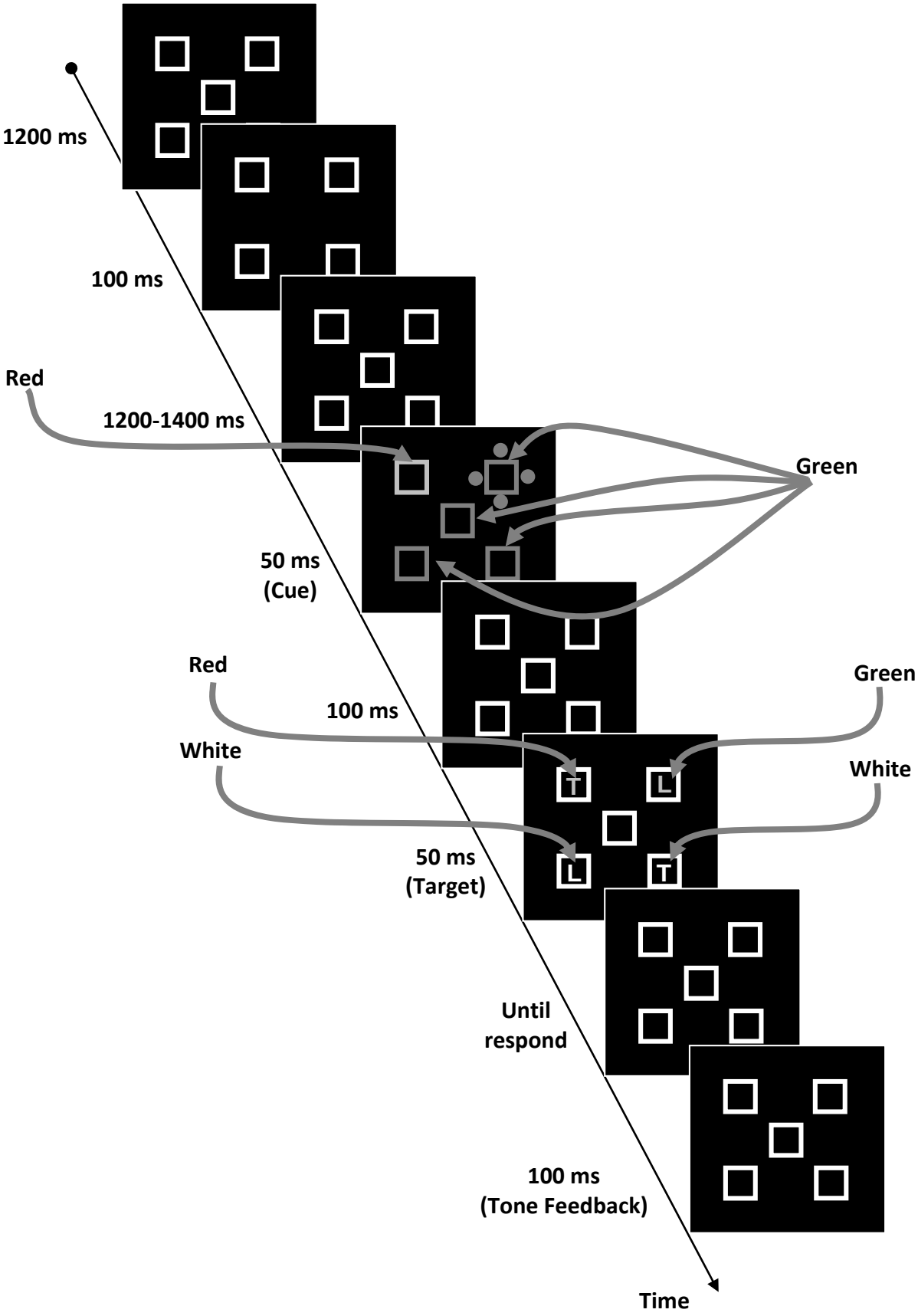

1200 ms
100 ms
Red
1200-1400 ms
Green
50 ms
(Cue)
Red
Green
100 ms
White
White
T
L
L
T
50 ms
(Target)
Until
respond
100 ms
(Tone Feedback)
Time

Figure 3

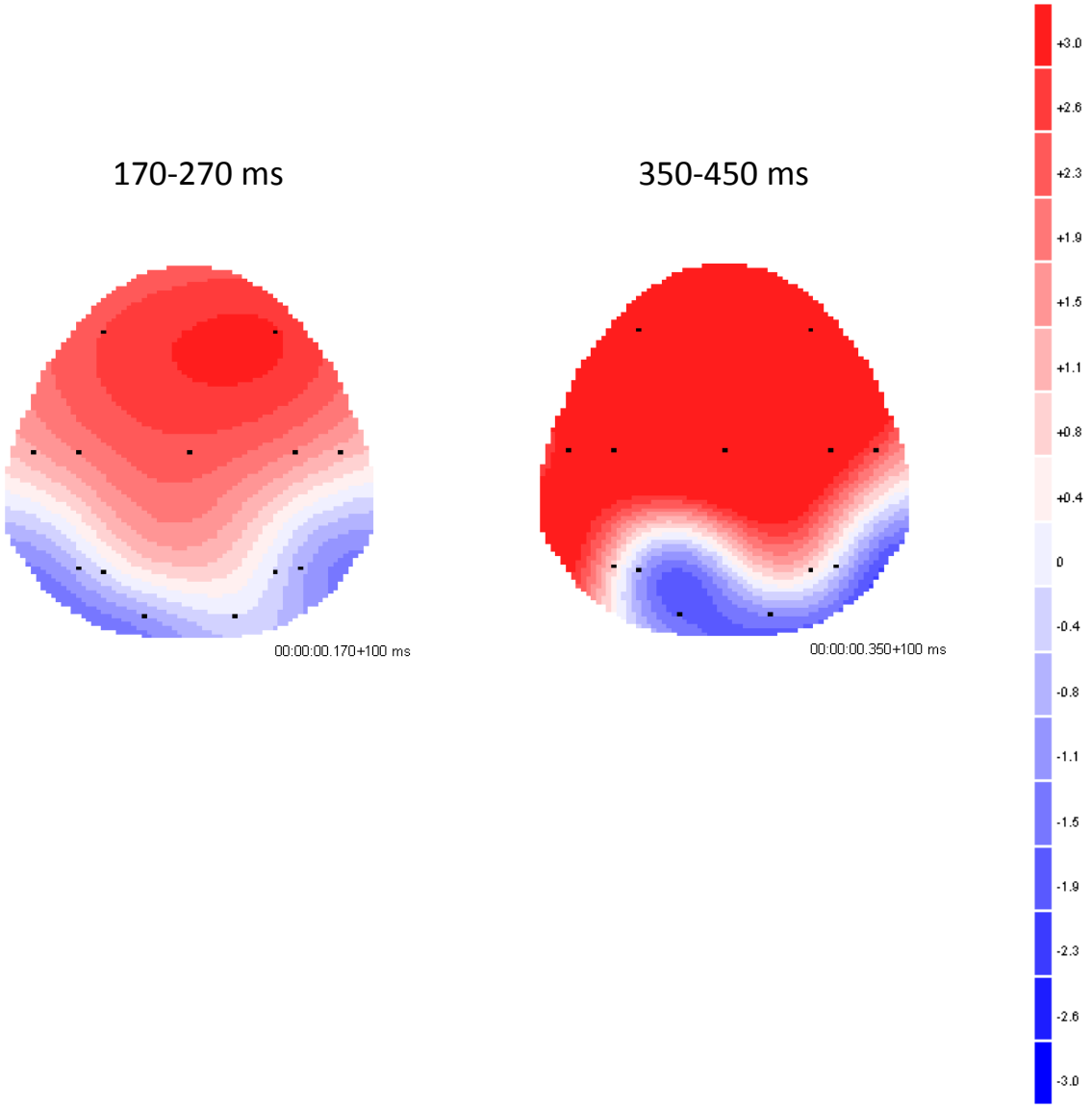

170-270 ms
350-450 ms
00:00:00.170+100 ms
00:00:00.350+100 ms
+3.0
+2.6
+2.3
+1.9
+1.5
+1.1
+0.8
+0.4
0
-0.4
-0.8
-1.1
-1.5
-1.9
-2.3
-2.6
-3.0

Figure 4

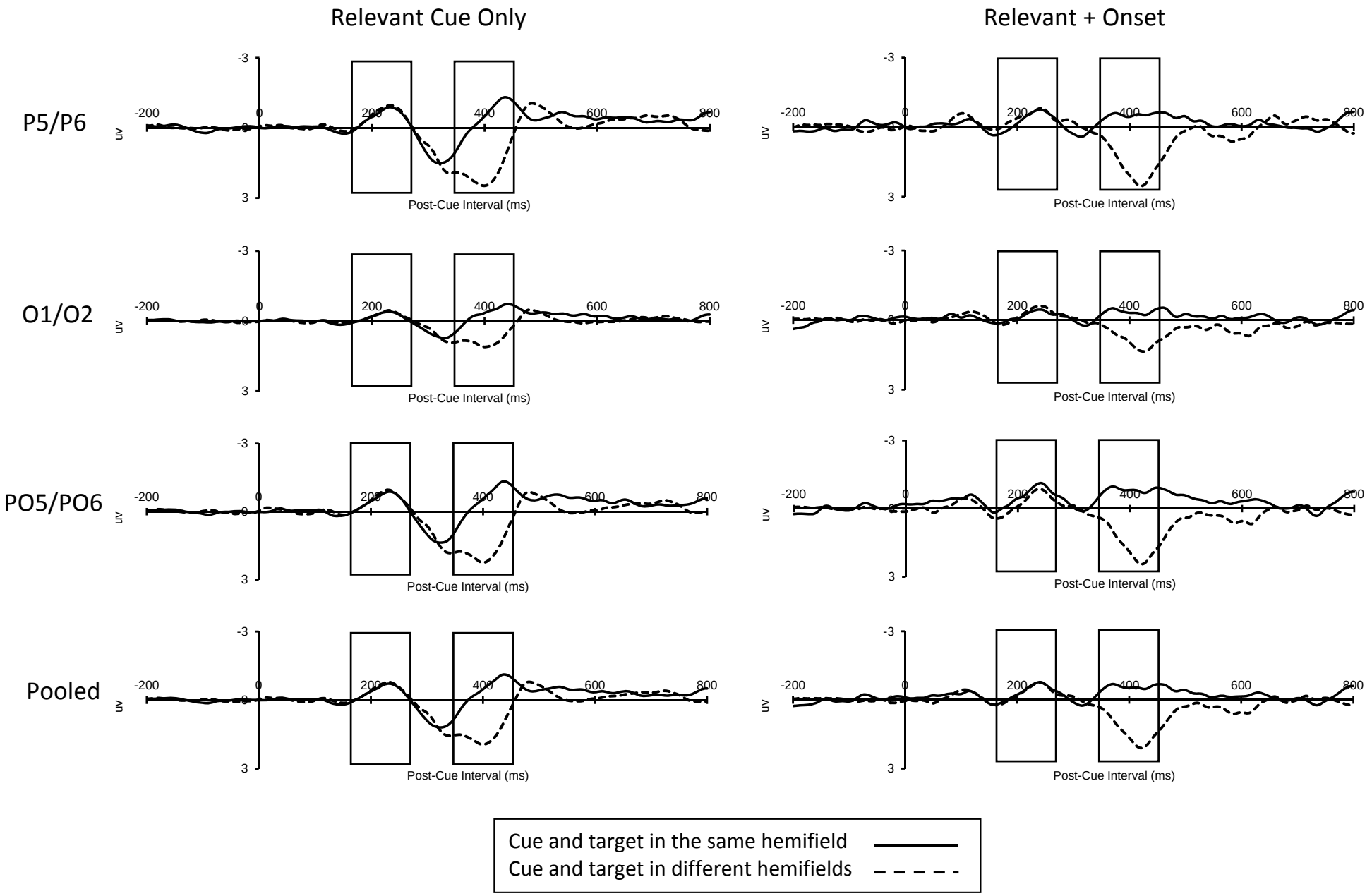

Relevant Cue Only
Relevant + Onset
P5/P6
O1/O2
PO5/PO6
Pooled
-3
3
uv
-200
0
200
400
600
800
Post-Cue Interval (ms)
Cue and target in the same hemifield
Cue and target in different hemifields

Figure 5

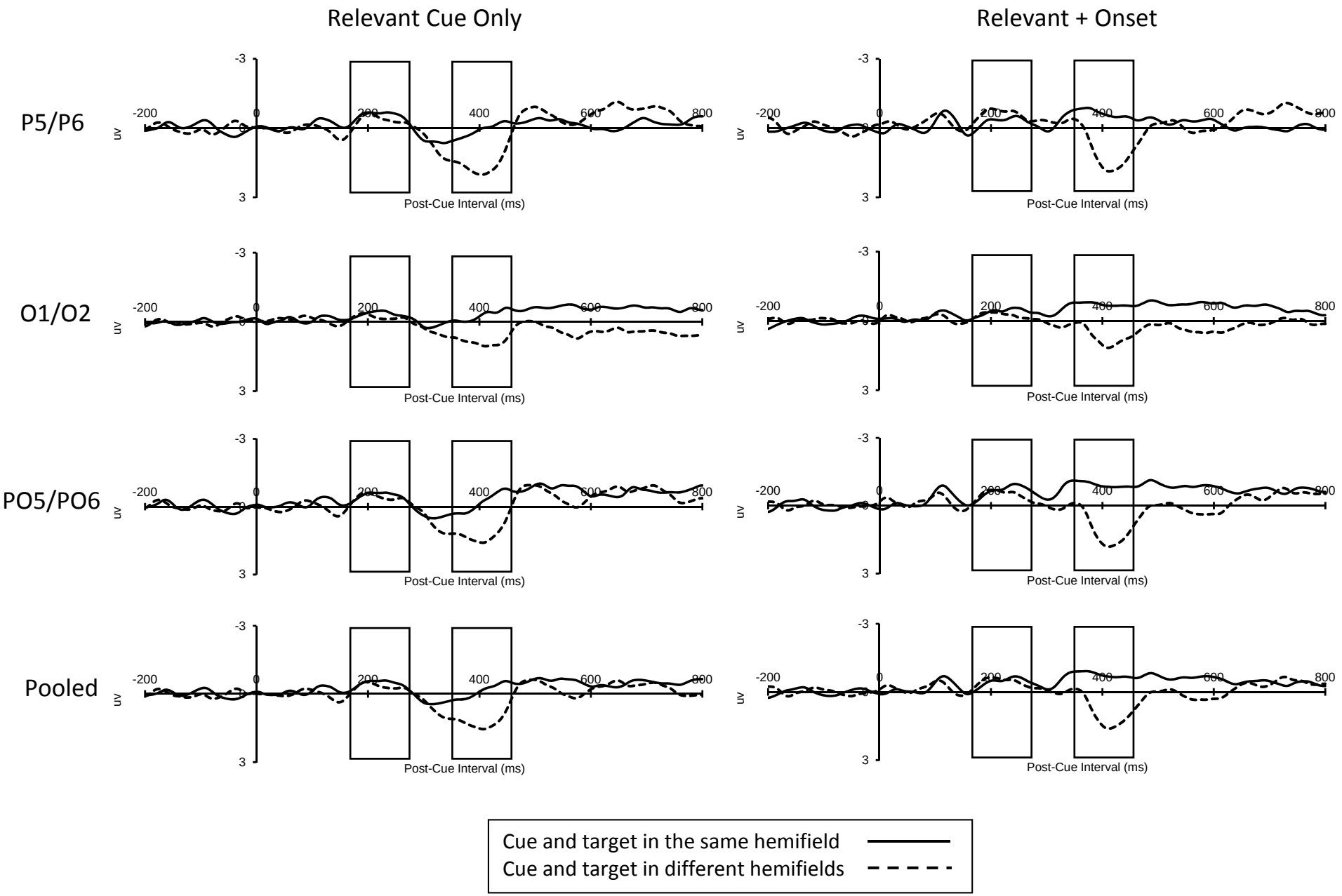

Relevant Cue Only
Relevant + Onset
P5/P6
O1/O2
PO5/PO6
Pooled
-3
3
uv
-200
0
200
400
600
800
Post-Cue Interval (ms)
Cue and target in the same hemifield
Cue and target in different hemifields

Figure 6

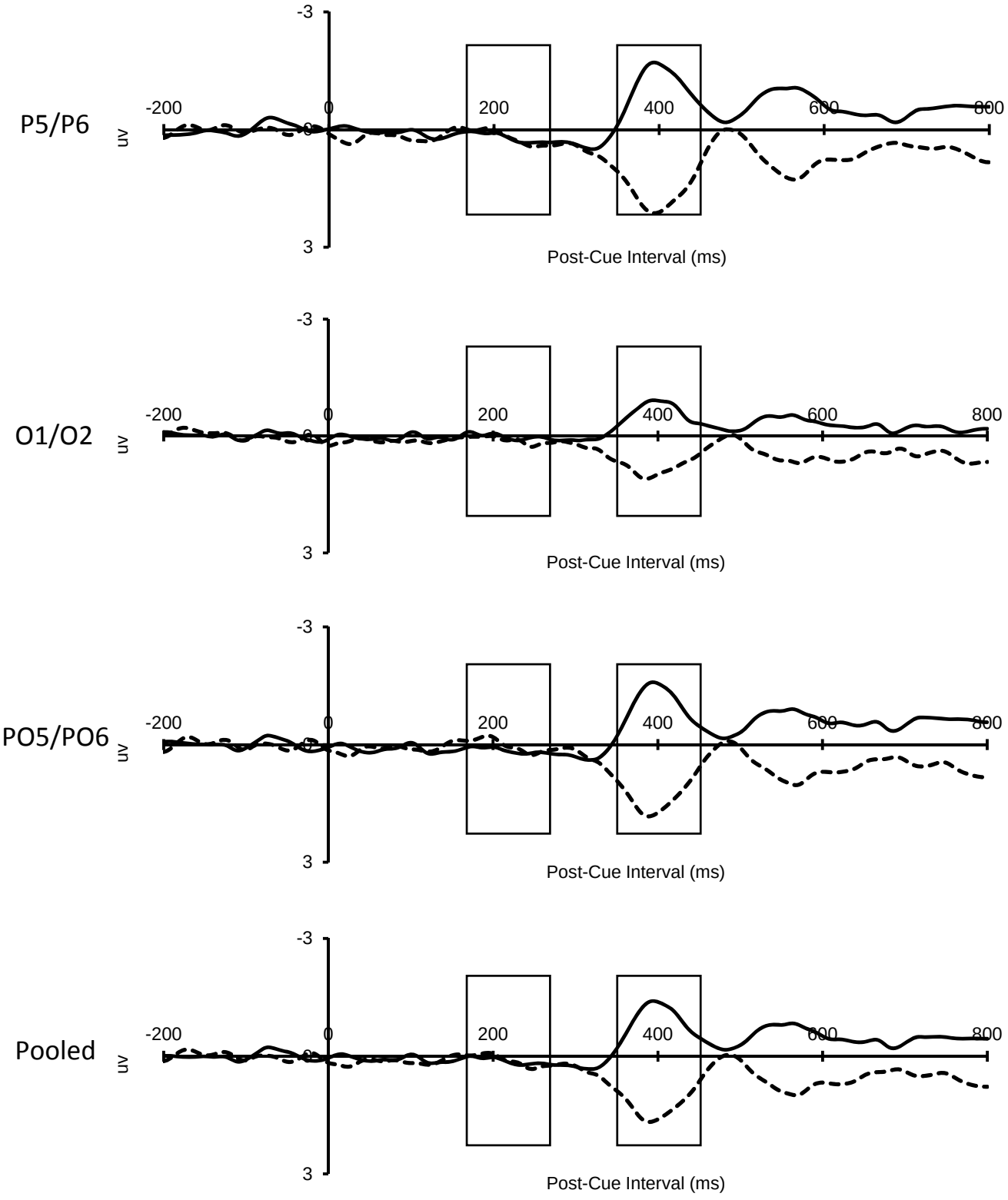
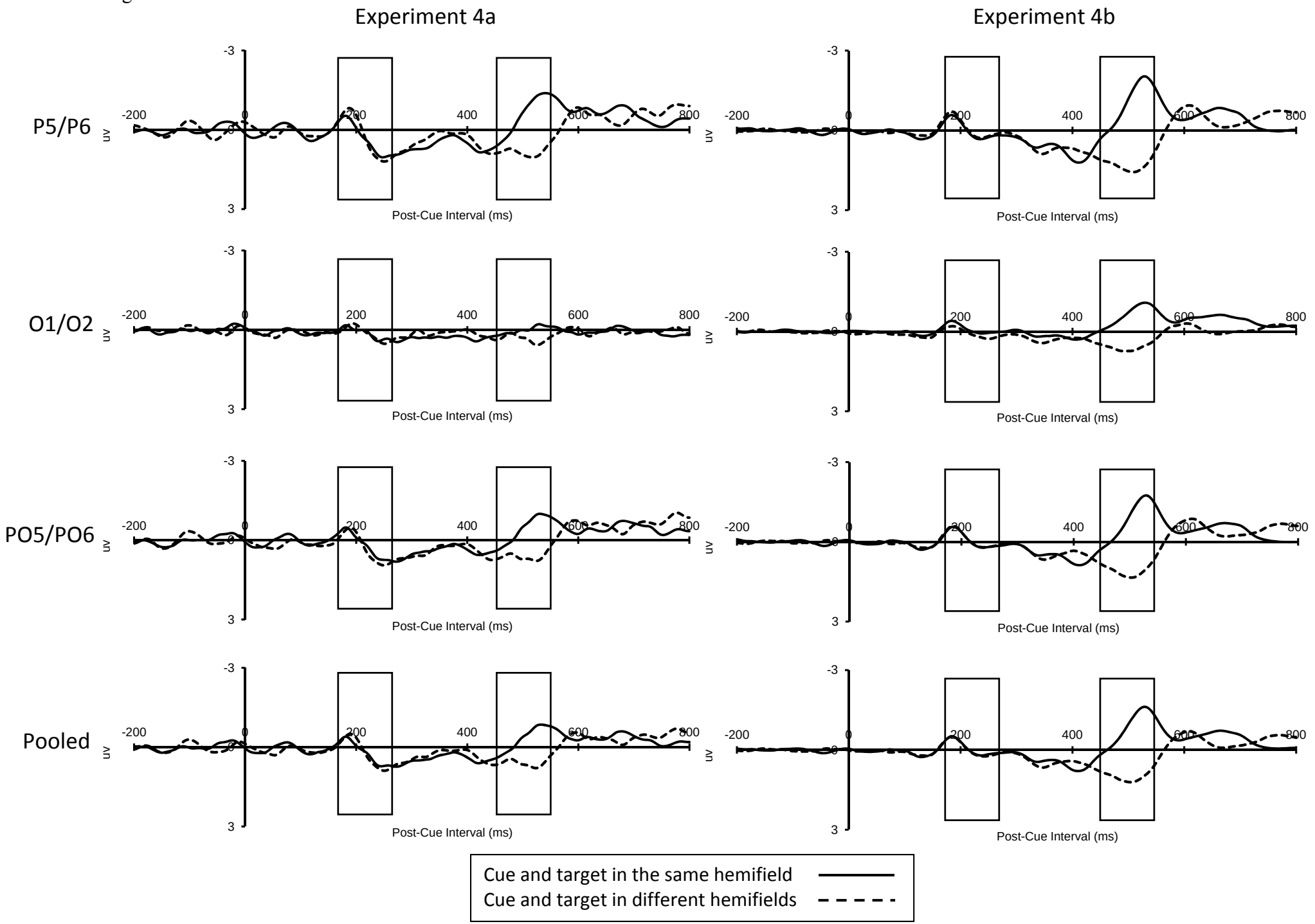

P5/P6
O1/O2
PO5/PO6
Pooled
uv
-3
3
-200
0
200
400
600
800
Post-Cue Interval (ms)
Cue and target in the same hemifield
Cue and target in different hemifields

Figure 7


Experiment 4a
Experiment 4b
P5/P6
O1/O2
PO5/PO6
Pooled
-3
3
uv
-200
0
200
400
600
800
Post-Cue Interval (ms)
Cue and target in the same hemifield
Cue and target in different hemifields