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Contingent Attentional Capture by Top-Down Control Settings: Converging Evidence From Event-Related Potentials

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Theories of attentional control are divided over whether the capture of spatial attention depends primarily on stimulus salience or is contingent on attentional control settings induced by task demands. The authors addressed this issue using the N2–posterior–contralateral (N2pc) effect, a component of the event-related brain potential thought to reflect attentional allocation. They presented a cue display followed by a target display of 4 letters. Each display contained a green item and a red item. Some participants responded to the red letter and others to the green letter. Converging lines of evidence indicated that attention was captured by the cues with the same color as the target. First, these target-color cues produced a cuing validity effect on behavioral measures. Second, distractors appearing in the cued location produced larger compatibility effects. Third, the target-color cue produced a robust N2pc effect, similar in magnitude to the N2pc effect to the target itself. Furthermore, the target-color cue elicited a similar N2pc effect regardless of whether it competed with a simultaneous abrupt onset. The findings provide converging evidence for attentional capture contingent on top-down control settings.

Keywords: attentional capture, N2pc effect, spatial attention

In complex visual environments, goal-directed behavior requires that we attend selectively to relevant sources of information. Most current theories of visual attention acknowledge two distinct modes of attentional control (e.g., Bundesen, 1990; Cave & Wolf, 1990; Duncan & Humphreys, 1989; Jonides, 1981; Posner, 1980). One type is the voluntary (*endogenous*; top-down driven) direction of attention that occurs when the observer intentionally selects a portion of visual information to perform. Another is the involuntary (*exogenous*; bottom-up driven) capture of attention by new stimuli or changes in stimuli. Combined, these two modes achieve a compromise between focusing on the current task and responding rapidly to new opportunities or new dangers (see Folk, Remington, & Johnston, 1992).

The present study examined what factors drive the involuntary capture of attention (i.e., the exogenous component). One popular view is that certain types of very salient stimuli, such as bright lights or abrupt onsets, can capture attention irrespective of the observer's goals (e.g., Theeuwes, 1991, 1994).[1] A concrete real-world example is a flashing light that captures an air traffic controller's attention while monitoring flights on the radar display. An opposing view is that capture depends not on stimulus salience but rather on what properties the observer is looking for in a given situation (i.e., on the *attentional control settings*; see Folk et al., 1992; Yantis & Jonides, 1990). When one looks for a friend in a red jacket, for example, other red objects might capture attention, but nonred abrupt onsets, however salient, would not.

Supporters of each view have offered a variety of evidence (discussed next), but no consensus has yet emerged. With the present study we aimed to shed additional light on the contributions of stimulus salience and top-down control settings to involuntary attention capture, using a combination of behavioral and electrophysiological measures.

Stimulus Salience Versus Contingent Attentional Capture

The hypothesis that attention can be captured by salient stimuli (e.g., abrupt onsets) irrespective of the observer's intentions or

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[1] Previous studies have shown attentional capture by properties of the stimulus array, such as abrupt luminance transients (e.g., Yantis & Jonides, 1984), salient stimulus difference (e.g., Theeuwes, 1991), or new perceptual objects (e.g., Yantis & Hillstrom, 1994). The present study was not designed to examine which types of stimulus properties capture attention but rather focused on the relative contributions to attentional capture by stimulus properties versus top-down control settings. Thus, we used the expression "attentional capture by stimulus salience" to refer to any cases in which attentional capture by an object is driven by stimulus properties, irrespective of the observer's intentions or the task demands.

goals (i.e., involuntarily) has been supported by a variety of studies using a variety of paradigms (e.g., the cuing paradigm of Jonides, 1981; the visual search paradigm of Theeuwes, 1991, 1992, and Yantis & Jonides, 1984, 1990). For instance, to determine whether abrupt onsets capture visual attention, Yantis and Jonides (1984; Experiment 1) had participants detect the presence of a specified target (e.g., the letter *P*) in a visual display. The critical manipulation was how the stimuli appeared: One object had an abrupt onset whereas the remaining object(s) were revealed by gradually removing camouflaging premasks. When the target did not have an abrupt onset, response time (RT) increased substantially as the display set size increased from 2 to 4. When the target did have an abrupt onset, however, the effect of display set size was very small. These data suggest that even though the abrupt onset was no more likely to be the target than any other item, it consistently captured attention first. Even stronger evidence that capture is truly involuntary (against the observer's will) comes from a study by Remington, Johnston, and Yantis (1992).[2] They found evidence of capture even when the abrupt onset in a cue display, presented just prior to the target display, never validly cued the target location (i.e., even when capture was always counterproductive).

Theeuwes (1994; see also 1991, 1992), using a visual search paradigm, has provided evidence for involuntary attentional capture by other salient stimulus properties, such as singletons (an item that stands out because it does not have a certain feature possessed by all of the other items). In these experiments, participants were asked to respond to the orientation of a line segment (horizontal vs. vertical) appearing (a) inside a red circle among green circles (the color condition) or (b) inside a green circle with an abrupt onset among green circles without an abrupt onset (the onset condition). In half of the color condition blocks, one of the green distractor circles had an abrupt onset. Similarly, in half of the onset condition blocks, one of the no-onset distractor circles was red (all others were green). Theeuwes found that in both the color and the onset conditions, the presence of an irrelevant singleton in a nontarget location delayed the response to the target. He therefore concluded that attention capture depends strongly on the relative salience of the singletons presented in the visual field.

Although these studies indicate that salient stimulus properties sometimes capture attention involuntarily, Folk et al. (1992) questioned whether this capture is driven purely by stimulus salience. They pointed out that previous studies demonstrating capture by abrupt onsets used displays in which the target itself was an abrupt onset. It is conceivable, therefore, that abrupt onsets captured attention only because participants had set themselves to look for abrupt onsets. The paradoxical possibility that capture is involuntary yet depends on top-down control settings is commonly known as the *contingent capture hypothesis*.

To test the contingent capture hypothesis, Folk et al. (1992; Experiment 3) independently manipulated the type of cue and the type of target. They proposed that cues would capture attention only if they matched the property used to find the target. In the *onset target* condition, a single character (*X* or an equals sign) appeared abruptly in one of four boxes; in the *color target* condition, a character was presented in each of the four boxes, but one character (the target) was red. Just before the target display, a cue display appeared, consisting of small white dots surrounding one or more of the boxes. In the *onset cue* condition, dots appeared abruptly around only one of the boxes; in the *color cue* condition, dots were presented around all four boxes, but one set of dots was red. The "cues" actually provided no information about target location in this experiment; the target appeared in the cue location 25% of the time (valid trials) and in one of the other three locations 75% of the time (invalid trials). The critical dependent measure was the cuing validity effect, defined as RT on invalid trials minus RT on valid trials. The assumption is that capture to the location of the cue would produce slower responses on invalid trials (because attention is directed away from the target) than on valid trials. The key finding is that onset cues produced a cuing validity effect (evidence of attention capture) in the onset target condition but not the color target condition. Similarly, the color cues produced a cuing validity effect in the color target condition but not the onset target condition.

Folk et al. (1992) concluded that salient stimuli do not have the inherent power to capture attention. Instead, capture depends critically on the match between stimulus properties and the observer's control settings. Even a feature that is not especially salient could, in principle, capture attention if the observer were looking for such a feature. This hypothesis is counterintuitive in that even though capture is involuntary and triggered by the stimulus (bottom-up), it nevertheless depends critically on top-down task settings. As a real-world analogy, the action of a thermostat (e.g., turning on heat) is stimulus driven (based on the temperature falling or rising) yet depends on a top-down setting (the critical temperature threshold). Several other studies have subsequently supported this hypothesis (e.g., Atchley, Kramer, & Hillstrom, 2000; Bacon & Egeth, 1994; Folk & Remington, 1999; Folk, Remington, & Wright, 1994; Gibson & Amelio, 2000; Gibson & Kelsey, 1998; Pashler, 2001; Yantis & Egeth, 1999).

Although these studies provide compelling evidence that stimulus-driven attentional capture can be contingent on top-down attentional control settings, there are seemingly conflicting findings. If participants know the location of an upcoming target, then one might assume that top-down control would limit search to that specific location. If so, abrupt onsets in other locations should not capture attention. Contrary to this prediction, several studies have found that foreknowledge of the target location does not prevent abrupt onsets in distractor locations from capturing attention (e.g., Müller & Rabbitt, 1989; Remington et al., 1992; but see also Theeuwes, 1991; Yantis & Jonides, 1990). Thus, the influence of top-down control settings may be limited.

Even more serious criticisms of the contingent capture hypothesis have been raised. As noted above, Folk et al. (1992) concluded that abrupt onsets did not capture attention because they did not produce a cuing effect: RT did not depend on whether the target appeared in the onset location (valid trials) or some other location (invalid trials). This finding, however, leaves open the possibility that attention briefly shifted to the location of the onset but was quickly redirected back to a neutral position before the target appeared (see Remington, Folk, & McLean, 2001; Theeuwes,

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[2] Capture is sometimes said to occur *automatically*. However, this term implies that capture is not only involuntary but (among other things) requires no limited resources. Capture studies directly support the claim of involuntariness but do not necessarily provide evidence for other meanings of the word *automatically*. Therefore, following Folk et al. (1992), we refer to capture as being *involuntary*, not as being *automatic*.

Atchley, & Kramer, 2000). Indeed, some studies have provided evidence that when salient distractors do capture attention (e.g., early in practice or when distractors are far from the target), they cause an early shift of attention followed by a redirection of attention back to the target (e.g., Kim & Cave, 1999; but see Lamy, Tsal, & Egeth, 2003). Likewise, the presence of a cuing validity effect for color cues does not prove that attention actually moved to the location of the color cue. It is possible that when the cue and target (both of which contain the feature used to locate targets) appear in different locations, the decision about where to direct attention is prolonged (a type of filtering cost; see Remington et al., 2001). For instance, when the target is defined by its redness, a red cue might fail to capture attention but nevertheless slow the decision of which red object is the target. Such a prolongation could, by itself, explain the cuing effect on RT (for a rebuttal, see Remington & Folk, 2001; Remington et al., 2001).

These criticisms highlight the fact that overall RT is an indirect indicator of the locus of attention. To get around this problem, the present study investigated attention capture using event-related potentials (ERPs), which can provide continuous measures of attentional allocation.

An Electrophysiological Index of the Locus of Spatial Attention

Attentional allocation to visual objects has been found to produce an increase in negative voltage in the brain potentials over posterior scalp about 200–300 ms after stimulus onset (e.g., Luck & Hillyard, 1990, 1994). This ERP component, known as the *N2pc effect* (short for N2–posterior–contralateral), is lateralized (see Figure 1 for an illustration). That is, the ERP at a given electrode in the left hemisphere is more negative when attention is directed to a stimulus in the right visual field (contralateral) as compared with the left visual field (ipsilateral). Likewise, the ERP at a given electrode in the right hemisphere is more negative when attention is directed to a stimulus in the left visual field (contralateral) as compared with the right visual field (ipsilateral). Thus, as an index of attention to a lateralized stimulus, the N2pc effect can be quantified as the average difference between the contralateral potentials and ipsilateral potentials.

Previous electrophysiological studies have suggested that the N2pc effect specifically reflects the attentional suppression of competing information from nearby distractors with the potential to interfere with target identification (see, e.g., Luck & Hillyard, 1990, 1994; Woodman & Luck, 1999). For instance, Luck and Hillyard (1994) found that the N2pc effect was absent when the distractors could easily be rejected on the basis of a single feature and thus distractor suppression was unnecessary. Eimer (1996) has argued, however, that the N2pc effect may not reflect attentional suppression of the distractors per se but rather selective processing of relevant information. Despite these subtly different interpretations of the N2pc effect, there is general agreement that the N2pc effect is associated with attentional allocation to a visual object and that it can provide an extremely useful tool for directly assessing the locus of spatial attention.

The N2pc effect has obvious advantages over behavioral measures (e.g., RT) for the study of spatial attention and, in our case, attention capture. In particular, the N2pc effect provides a continuous indicator of the locus of attention. Thus, we can observe not only whether attention was captured by objects in the left or right hemifield but when attention was captured. As an example, a brief delay in attention capture by a cue (say, 100 ms) might not be detectable in RT to a target presented 150 ms later, assuming that attention can be redirected before the target appears. Such a delay, however, would necessarily be reflected in the N2pc effect to the cue. Likewise, there are many ways for a cue to influence RTs without actually capturing spatial attention (e.g., Prinzmetal, McCool, & Park, 2005). A finding of an N2pc effect to a cue would provide much more direct evidence of an actual shift of spatial attention to the location of the cue.

Recently, Hickey, McDonald, and Theeuwes (2006) used the N2pc effect to study attentional capture using a visual search paradigm. In their experiments, search items consisted of 10 shapes with oriented lines inside them, arranged in a circle around the central fixation point. Participants performed a visual search task in which they responded to the orientation of the line inside the unique shape (e.g., the diamond among nine circles), known as the singleton target. On some trials, a salient but irrelevant color singleton appeared simultaneously with the shape singleton. The main question was whether the salient color singleton would capture attention despite being irrelevant.

Hickey et al. (2006) observed an N2pc effect to an irrelevant-color singleton, on the left or right side of the display, when the target was presented on the vertical meridian (so that it should produce no lateralized N2pc effect itself). Furthermore, in Experiment 2, they observed a small but significant N2pc effect to the lateralized irrelevant-color singleton when presented in the opposite hemifield as the shape singleton (the target). Because the color singleton was assumed to be more salient than the shape singleton, Hickey et al. concluded that attention is captured involuntarily by the most salient singleton, regardless of the top-down control settings.

Hickley et al.'s (2006) findings are certainly consistent with capture based on stimulus salience. It could be argued, however, that their paradigm encouraged participants to look for any singleton object (see, e.g., Bacon & Egeth, 1994; Lamy et al., 2003). Perhaps it is easier to find a singleton (regardless of the type) than it is to find a singleton along a specific dimension. Even on trials where two singletons were presented, capture by all singletons would at least reduce the search set size from 10 to 2. If participants were in fact searching for any singleton, then the color singleton captured attention only because it matched the current attentional control settings (i.e., looking for singletons). The goal of the present study was to address this issue with even tighter control over the participants' attentional control settings.

The Present Study

The present experiments used a task-cuing paradigm. All participants viewed the same displays (see Figure 2 for an example), containing both red and green items, but some participants were instructed to search for the green letter in the target display and some were instructed to search for the red letter. Experiment 1 verified that attention to targets in the left or right visual field produces an N2pc effect in the contralateral hemisphere. Experiment 2 then examined whether an irrelevant cue (composed of four dots) would capture attention (as indexed by the N2pc effect) when it had the color (red or green)

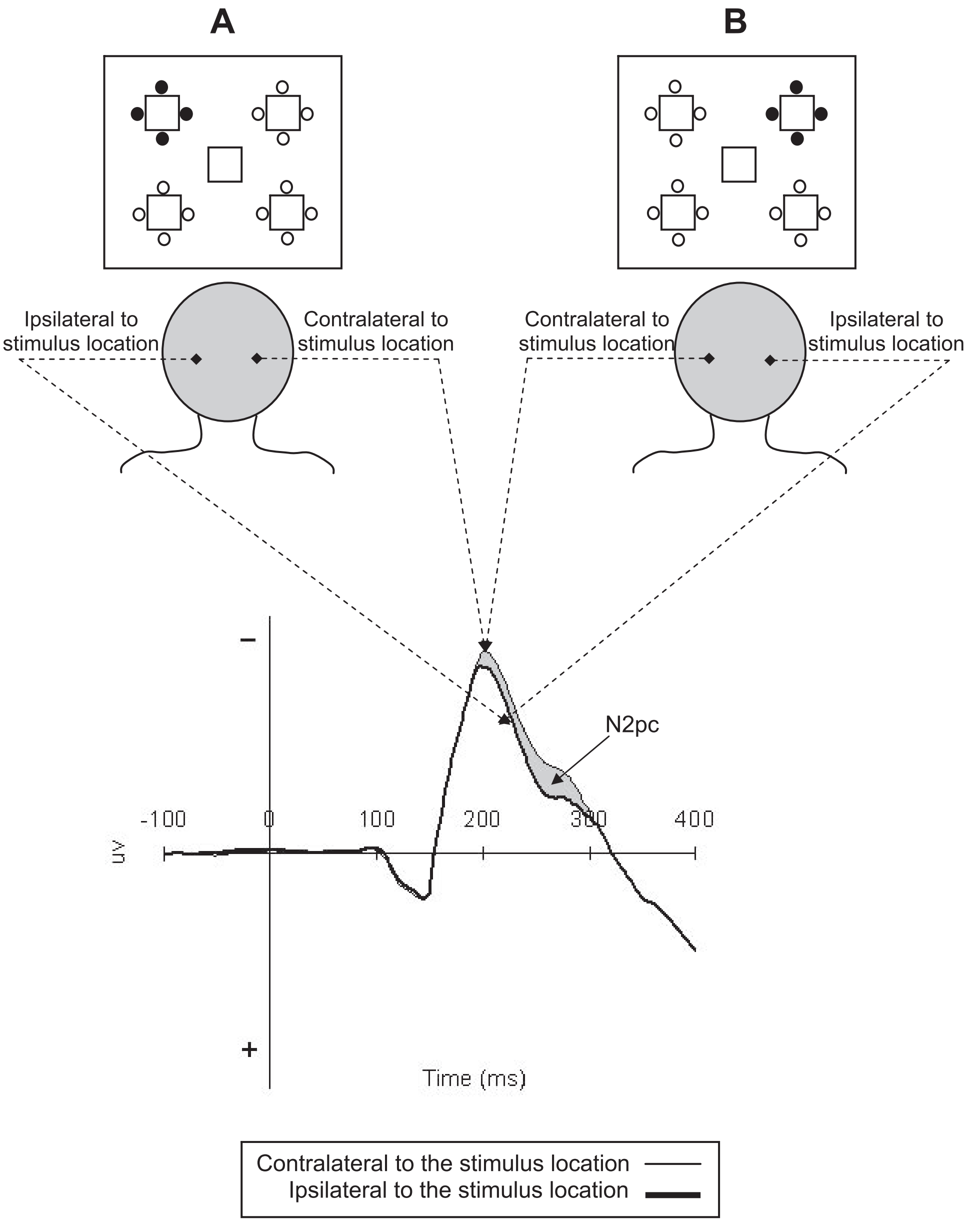

Figure 1. A hypothetical N2–posterior–contralateral (N2pc) component produced when attention is allocated to a stimulus (the filled dots in this case) in the left visual field (Panel A) or the right visual field (Panel B). Roughly 200–300 ms after stimulus onset, the event-related potentials are more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

that participants were looking for in the target letter display. Experiment 3 examined whether attention capture by a color cue is prevented or delayed by the simultaneous presence of an abrupt onset elsewhere in the visual field.

Experiment 1

Experiment 1 was designed to establish that our target produces an N2pc effect and to estimate the time course of that N2pc effect in our experimental paradigm. To isolate the N2pc effect to the target, we used a neutral cue display that contained a homogeneous display of four white dots around each of the four possible stimulus locations (so that there was no reason for attention to be captured to one particular location). The neutral cue display was not strictly necessary, but we included it to make the event sequence similar to that of the subsequent two experiments (both of which did include a cue display).

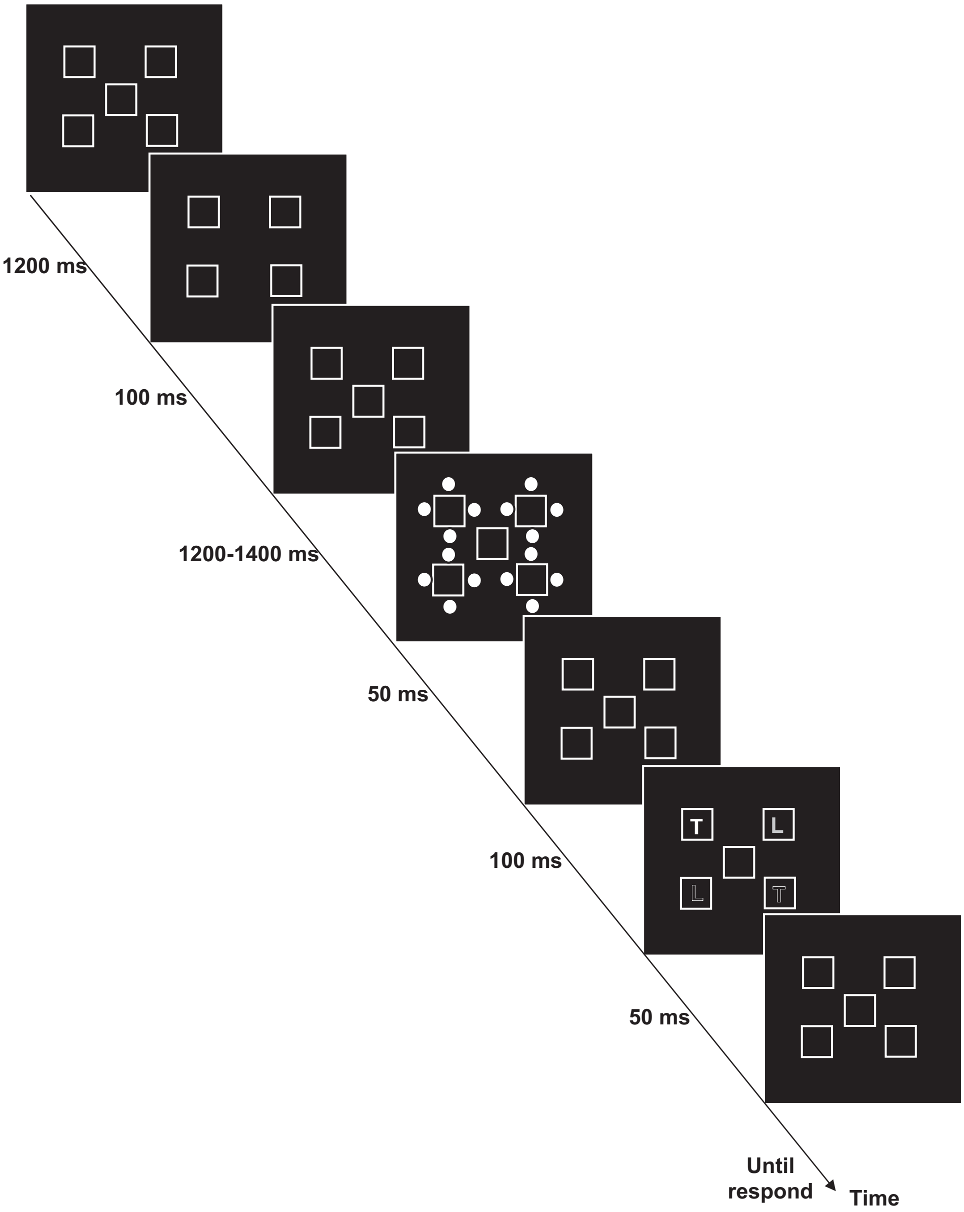

Figure 2. An example event sequence in Experiment 1. In the real experiment, the stimuli were colored. In this example target display, the top-left letter *T* would be red, the bottom-left letter *L* would be white, the top-right letter *L* would be green, and the bottom-right letter *T* would be white.

Method

Participants. Nine undergraduate students from Oregon State University participated in exchange for extra course credit. Data from 1 participant were excluded from the final data analyses owing to excessive eye movement artifacts in the electroencephalographic data (see below for details). All had normal or corrected-to-normal vision.

Apparatus and stimuli. Stimuli were presented on IBM-compatible microcomputers connected to 19-in. ViewSonic monitors and E-prime response boxes. The average viewing distance was about 55 cm.

Within each trial, three stimulus events were presented in succession (see Figure 2). The first was the fixation display, consisting of five boxes: a center box surrounded by four peripheral boxes placed at the corners of an imaginary square (top left, bottom left, top right, and bottom right). Each peripheral box was equidistant from the center box (7.66°, center to center) and from adjacent peripheral boxes (10.81°, center to center). Each box was 2.39° × 2.39°, drawn with thin (0.10°) white lines.

The cue display consisted of the fixation display with four additional white, filled circles around each of the four peripheral boxes. The dots were arranged in a diamond configuration, as shown in Figure 2. The circles, which were 1.04° in diameter, were placed 0.31° from the edge of the box.

The target display consisted of the fixation display plus the addition of a letter (1.04° wide × 1.35° long × 0.31° thick in Arial font) inside each of the four peripheral boxes. Each hemifield (left vs. right visual field) contained one *T* and one *L*. One of the letters was red, one was green, and two were white, with the restriction that the red and green items were always located in different 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). The cue display (consisting of four white, filled circles surrounding each of the four peripheral boxes) appeared for 50 ms and then was 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.

Half of the participants were instructed to respond to the identity of the red letter and the other half were instructed to respond to the identity of the green letter. Participants were to press the leftmost response-box button with their left index finger for the letter *T* and the rightmost button with their right index finger for the letter *L*. They were asked to respond quickly and accurately. Immediately after a response was recorded, the next trial began with the 1,200-ms fixation display.

Participants performed one practice block of 32 trials, followed by 16 experimental blocks of 64 trials each (a total of 1,024 experimental trials). After each block, participants received a summary of their mean RT and accuracy and were encouraged to take a break. The entire session lasted approximately 2 hr, with the computerized experiment lasting about 70 min.

Electroencephalographic (EEG) recording and analyses. The EEG activity was recorded using Q-cap AgCl electrodes 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 (see Luck, 2005). The horizontal electrooculogram (HEOG) was recorded bipolarly from electrodes at the outer canthi of both eyes, and 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 band pass of 0.1–100 Hz. The amplified signals were digitized at 500 Hz.

Trials with possible ocular artifacts were identified in two steps. First, trials with ocular artifacts were rejected automatically using a threshold of ±75 μV for a 1,000-ms epoch beginning 200 ms before cue onset to 800 ms after cue onset (i.e., 650 ms after target onset). Next, each of these candidate artifact trials was then inspected manually. To determine whether individual participants systematically moved their eyes in response to the target stimulus, we computed for each participant average HEOG waveforms for left-target and right-target trials, separately, during the period 400–500 ms after the neutral cue onset (i.e., 250–350 ms after target onset). Following Woodman and Luck (2003), we included in the data analyses only participants whose average HEOG activity was less than ±3 μV during this time window. We excluded 1 participant for this reason. See Figure 3 for a plot of the average HEOG for left targets and right targets for all remaining participants. Among the 8 participants included in the final data analyses, ocular artifacts led to the rejection of 16.63% of trials, with no more than 25% rejected for any individual participant.

To quantify the overall magnitude of the N2pc effect, we focused on the time window 250–350 ms after target onset (i.e., 400–500 ms after the onset of the neutral cue), which (on the basis of previous studies and pilot data) was most likely to show a strong

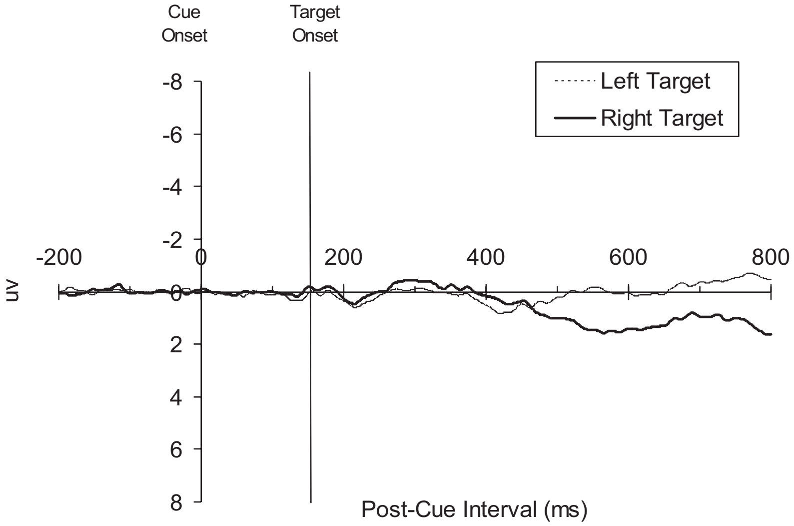

Figure 3. Grand average event-related brain potentials for the horizontal electrooculogram for targets appearing in the left hemifield and targets appearing in the right hemifield in Experiment 1. Negative is plotted upward, and time zero represents neutral cue onset. The target onset (represented by a solid vertical line) was 150 ms after the neutral cue onset.

N2pc effect. Specifically, the N2pc effect was measured as mean amplitude during this time window for all electrode sites contralateral to the target location (e.g., collapsed across the O1, PO5, and P5 electrode sites when the target was in the right hemifield) minus mean amplitude for all electrode sites ipsilateral to the target location (e.g., collapsed across the O2, PO6, and P6 electrode sites when the target was in the right hemifield), relative to the mean amplitude during a 200-ms precue baseline period. Analysis of variance (ANOVA) was used for all statistical analyses. The *p* values were adjusted using the Greenhouse–Geisser epsilon correction for nonsphericity, when appropriate (e.g., Experiment 3). In Experiment 1, the ERP data were analyzed as a function of electrode laterality (contralateral vs. ipsilateral to the target location) and target position (left hemifield vs. right hemifield). Each of the four subconditions contained a total of 256 trials before trials that fell outside our RT cutoff or showed ocular artifacts were rejected. Our primary interest was the main effect of electrode laterality (i.e., the N2pc effect): a difference in the mean amplitude for all electrode sites contralateral to the target location relative to all electrode sites ipsilateral to the target location.

Results

In addition to trials with ocular artifacts, we excluded trials from the final analyses of behavioral data (RT and proportion of errors; PE) and EEG data if the RT was less than 100 ms or greater than 2,000 ms (0.13% of trials). Trials were also excluded from RT and EEG analyses if the response was incorrect. An alpha level of .05 was used to ascertain statistical significance.

Behavioral data analyses. The primary purpose of this control experiment was to establish the time course of the N2pc effect. There were no factors of interest relevant to the behavioral data in this experiment, so we report only the mean data: the mean RT was 526 ms and the mean PE was .03.

ERP analyses. Figure 4 shows the average waveforms for the contralateral and ipsilateral electrode sites relative to the target location (collapsed across the left and right target locations). An N2pc was apparent during the critical time window, 250–350 ms posttarget (in Figure 4, this time period corresponds to 400–500 ms after the onset of the neutral cue), $F(1, 7) = 10.35$, $p < .05$, $MSE = 0.7083$, $\eta_p^2 = .60$. The ERP was more negative for sites contralateral to the target location than for those ipsilateral to the target location; the average N2pc effect was −0.957 μV. The N2pc effect was small and reversed when the target was in the left hemifield (0.858 μV) but was large when the target was in the right hemifield (−2.771 μV), $F(1, 7) = 8.61$, $p < .05$, $MSE = 3.0583$, $\eta_p^2 = .55$. No other effects were found to be significant.

Discussion

The main purpose of Experiment 1 was to establish that our target stimuli produce an N2pc effect and to estimate its time course in the absence of capture by any cues. The ERP data confirmed that an N2pc effect did occur, primarily in the time

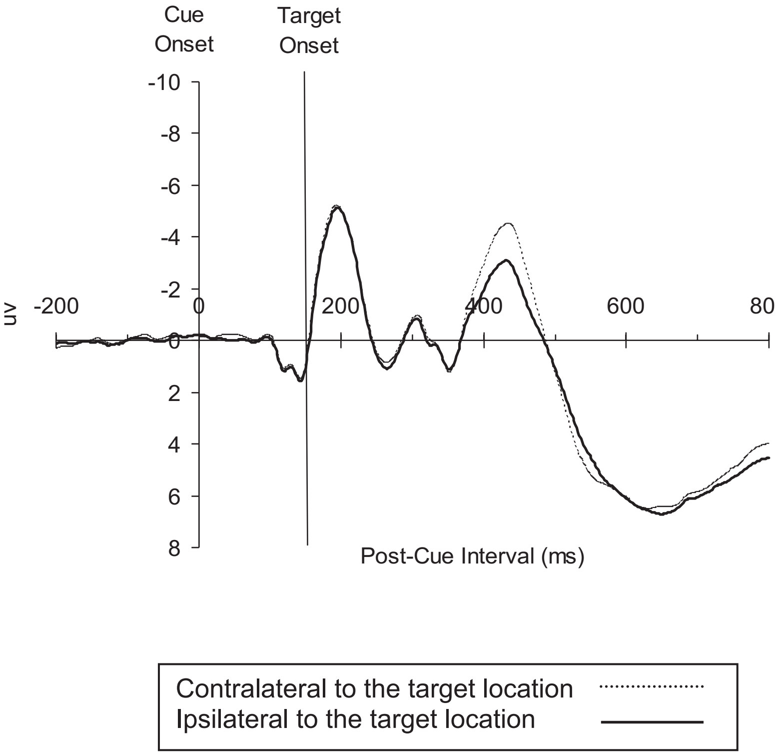

Figure 4. Grand average event-related brain potentials for the target, recorded and averaged across the posterior electrode sites contralateral or ipsilateral to the target location in Experiment 1. Negative is plotted upward, and time zero represents neutral cue onset. The target onset (represented by a solid vertical line) was 150 ms after the neutral cue onset.

window 250–350 ms after target onset (i.e., 400–500 ms after cue onset).

One might argue that the observed target-elicited N2pc effect occurred because physical differences between the target and distractor triggered differences in sensory or perceptual processing. This hypothesis can be ruled out because, overall, there were no physical differences between the target and the distractor. All participants received the same displays, but half were asked to respond to the red target and ignore the green distractor and the other half were asked to respond to the green target and ignore the red distractor. Thus, across participants, the targets and distractors both consisted of equal mixtures of red and green stimuli. The observed target-elicited N2pc effect, therefore, must be due to the impact of attention on how the stimuli were processed.

Experiment 2

The purpose of Experiment 2 was to examine whether involuntary attention capture depends on top-down attentional control settings. The experiment was identical to that of Experiment 1, except that we modified the cue display: We presented green dots around one box, red dots around another box, and white dots around the remaining two boxes. The question was whether attention would be captured by the colored dots that happened to match the color the participant was instructed to respond to in the target display. We henceforth refer to the set of dots drawn in the same color as the target as the *target-color cue* (e.g., red dots when responding to red targets), and we refer to the dots drawn in the other color that did not match the target color as the *ignored-color cue* (e.g., red dots when responding to green targets). We refer to the set of white-colored dots (of which there were two sets in the cue display) as the *neutral-color cue*.

Following Folk et al. (1992, Experiment 3), we manipulated whether the color cues were valid or invalid. On 25% of trials the target-color cue location was the same as the target location (the valid condition), and on 75% of trials the target-color cue location was different from the target location (the invalid condition). Thus, participants had no incentive to voluntarily shift attention to the target-color cue location. The ignored-color cue was also 25% valid and 75% invalid.

We used two different measures of capture: behavioral and electrophysiological. In the behavioral data, capture to the target-color cue location should result in a cuing effect: faster RT and lower PE when the target-color cue is in the same location as the upcoming target than when it is not. Furthermore, the target-color cue should enhance the compatible effects produced by distractors in that location (we describe this test in more detail below). As explained below, these two behavioral tests of attention capture require separate data analyses.

In the electrophysiological data, capture of attention to the target-color cue location should produce an N2pc effect. Thus, the ERP data analyses focused on two time windows: (a) the time window in which the target-color cue should produce an N2pc effect (200–300 ms after cue onset) and (b) the time window in which the target should produce an N2pc effect (400–500 ms after cue onset, which translates to 250–350 ms after target onset, as in Experiment 1).[3] When the target-color cue and target are in the same hemifield, the target-color cue and target should produce an N2pc effect in the same direction. When the target-color cue and target are in different hemifields, however, the polarity of the N2pc effect to the target-color cue should be opposite to that of the target.

Method

Participants. There were 12 participants, drawn from the same participant pool as in Experiment 1. None had participated in the previous experiment. Four participants' data were excluded because their averaged HEOG was larger than ±3 μV. Thus, only 8 participants' data were included in the final data analyses. As in Experiment 1, half of the participants were instructed to respond to the red letters and the other half were instructed to respond to the green letters.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except for the cue display. Instead of presenting four white dots around each box prior to the target display, as in Experiment 1, one set of dots was red, one set was green, and two sets were white. In a given trial, the green dots and red dots were always presented on different sides of the display (left vs. right).

The design generated three different types of cue conditions. In the valid condition (25% of trials), the location of the target-color cue was the same as the location of the target. The remaining trials (75%) constituted the invalid condition. However, for the purpose of measuring the N2pc effect, it is necessary to distinguish between trials in which the target-color cue was in the same hemifield as the target (the invalid/same-hemifield condition; 25% of trials) and trials in which they were in different hemifields (the invalid/different-hemifield condition; 50% of trials).

Results

The data analysis was similar to that of Experiment 1. Application of the RT cutoffs eliminated approximately 0.09% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 9.21% of trials but no more than 24% for any individual participant. The average HEOG activity did not exceed ±3 μV between 250 ms and 350 ms after target onset for any participant (see Figure 5 for the average HEOG for the left-target and right-target trials).[4]

Behavioral data analyses: Cuing validity effects. The behavioral data were analyzed as a function of target location. There

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[3] The time window for the target-elicited N2pc effect, suggested by the results of Experiment 1, was 400–500 ms after cue onset, which translates to 250–350 ms after target onset. It was clear, however, from the present results that we needed a slightly earlier time window, 200–300 ms after cue onset, for the cue display. The exact reason for the slightly different time courses is unclear but might relate to stimulus differences or to a slight refractoriness of attentional shift following the shift to the color cue. In any case, our main conclusions do not depend critically on the details of the time windows used in the data analyses.

[4] Because Experiments 2 and 3 also had a cue display, we needed to ensure that participants did not move their eyes in response to the cues. Therefore we examined the HEOG during both the time window following target onset and the time window following cue onset (200–300 ms after the color cue onset). Only participants with an average HEOG activity less than ±3 μV in both time windows were included in the final data analyses.

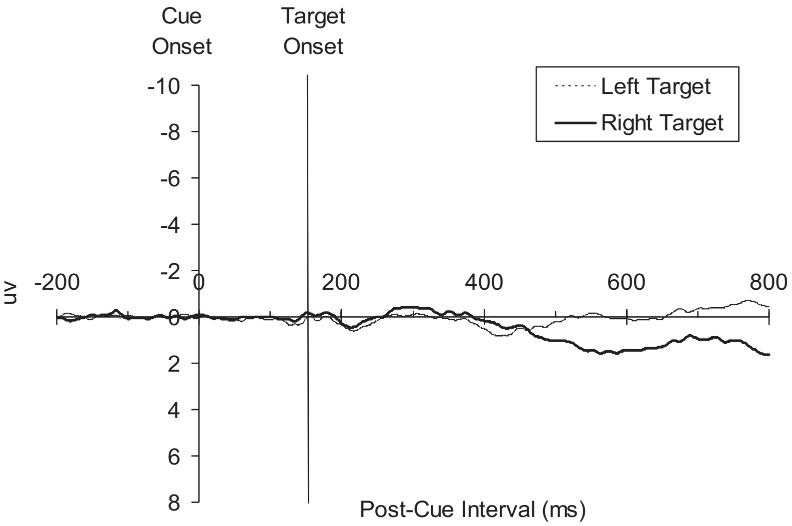

Figure 5. Grand average event-related brain potentials for the horizontal electrooculogram for targets appearing in the left hemifield and targets appearing in the right hemifield in Experiment 2. Negative is plotted upward, and time zero represents color cue onset. The target onset (represented by a solid vertical line) was 150 ms after the color cue onset.

were three possibilities. The target could appear in the location of the target-color cue, the location of the ignored-color cue, or the location of the neutral-color cue. Contingent capture predicts that performance should be best when the target appears in the location of the target-color cue and worst when it appears in any of the other locations (because a shift of attention from the cue location to the target location will be required). Table 1 shows the mean RT and PE for each of these conditions.

There was a main effect of target location on RT, $F(2, 14) = 41.10$, $p < .0001$, $MSE = 822$, $\eta_p^2 = .86$. Mean RT was 484, 534, and 538 ms when the target was in the target-color cue location, ignored-color cue location, and neutral-color cue location, respectively. Planned comparisons showed that RT was significantly shorter when the target was in the target-color cue location than when it was in any of the other locations; this is the traditional cue validity effect, often cited as evidence of attentional capture by a cue (in this case, by the target-color cue). However, RT when the target was presented in the ignored-color cue location was not significantly different from RT when the target was in a neutral-color cue location. Thus, only the cue presented in the target color captured attention, consistent with the contingent capture hypothesis.

The PE analyses supported the RT analyses. The main effect of target location on PE was significant, $F(2, 14) = 3.96$, $p < .05$, $MSE = 0.0012$, $\eta_p^2 = .32$; the mean PE was .018, .030, and .039 when the target was in the target-color cue location, ignored-color cue location, and neutral-color cue location, respectively. Planned comparisons on PE revealed that the only significant difference was that PE was lower when the target appeared in the target-color cue location than when it was in a neutral-color cue location.

Table 1
Mean Response Times (RTs) in Milliseconds and Proportion of Errors (PEs) in Experiment 2 as a Function of Target Location

Target location	RT	PE
Target-color cue location	484	.018
Ignored-color cue location	534	.030
Neutral-color cue location	538	.039

Behavioral data analyses: Compatibility effects. To provide converging behavioral evidence for attentional capture by the target-color cue, we examined the effects of compatible and incompatible distractors appearing at the cued location. This analysis was restricted to trials in which the target was not validly cued by either color cue (target color or ignored color). The basic logic is that if the target-color cue captures attention, then compatible distractor letters subsequently appearing at that location should produce an especially large reduction in RT to the target, whereas incompatible distractors at that target-color cue location should produce an especially large increase in RT to the target.

Consistent with contingent capture, the distractor at the location of the target-color cue produced a significant compatibility effect on RT (23 ms), $F(1, 7) = 34.78$, $p < .001$, $MSE = 60.19$, $\eta_p^2 = .83$, and a compatibility effect on PE (.024), albeit not a significant one, $F(1, 7) = 3.53$, $p = .1022$, $MSE = 0.0007$, $\eta_p^2 = .34$. However, the distractor at the location of the ignored-color cue produced no such effect; the effect on RT was –2 ms, $F < 1.0$, $\eta_p^2 = .04$, and the effect on PE was .009, $F(1, 7) = 9.08$, $p < .05$, $MSE = 0.00004$, $\eta_p^2 = .57$. To verify that these compatibility effects from the different types of color cues were significantly different, we performed a follow-up analysis. Note that it is not possible to directly compare these two effects in a cue type by compatibility ANOVA because these factors are not strictly orthogonal. Therefore, we performed the modified analysis described below.

Note that each display always contained two *T*s and *L*s, with one *T* and one *L* in each hemifield. Therefore, on every trial, one distractor letter was compatible with the target and two were

Table 2

Summary of Overall ANOVAs on the ERPs in Experiment 2 as a Function of Electrode Laterality (Contralateral or Ipsilateral to Target Location), Target-Color Cue Position (Left or Right Hemifield), and Target Position (Left or Right Hemifield) for the Cue- and Target-Elicited N2pc Time Windows

		200–300 ms (cue-elicited N2pc)			400–500 ms (target-elicited N2pc)		
Effect	*df*s	*F*	*MSE*	η_p^2	*F*	*MSE*	η_p^2
Electrode laterality (E)	1,7	2.61	0.300	.27	22.7**	1.247	.76
Target-color cue position (C)	1,7	16.06**	0.480	.70	< 1.0	0.898	.00
Target position (T)	1,7	1.04	0.317	.13	9.34*	0.561	.57
E × C	1,7	< 1.0	0.057	.03	< 1.0	0.070	.00
E × T	1,7	< 1.0	10.634	.04	< 1.0	12.310	.04
C × T	1,7	< 1.0	0.420	.01	< 1.0	1.234	.07
E × C × T	1,7	16.0**	0.844	.70	3.85	0.693	.35

Note. ANOVAs = analyses of variance; ERPs = event-related potentials; N2pc = N2–posterior–contralateral effect.
$^{*}p < .05$. $^{**}p < .01$.

incompatible. In the following analysis, we examined performance as a function of where the compatible distractor letter was located. It could appear at the location of the cue (dots) drawn in the color used to find the target (i.e., the target-color cue location), the location of the cue (dots) drawn in the opposite color (the ignored-color cue location), or one of the remaining two locations (the neutral-color cue location). So that compatibility effects would not be confounded with cue validity effects, we restricted this data analysis to trials in which the target appeared in a neutral-color cue location (i.e., one that contained white dots in the cue display).[5]

If the target-color cue captured attention, target RT should be faster when the compatible letter was presented at the target-color cue location as compared with the ignored-color cue location or a neutral-color cue location. The analyses confirmed this prediction. The overall effect of the location of the compatible letter was statistically significant, $F(2, 14) = 22.67$, $p < .0001$, $MSE = 229$, $\eta_p^2 = .76$. Planned comparisons showed that RT was significantly shorter when the compatible distractor letter appeared in the target-color cue location (516 ms) than when it appeared in the ignored-color cue location (548 ms) or in a neutral-color cue location (544 ms). RT was not significantly different between the ignored-color cue location and the neutral-color cue location. Thus, these data indicate that the target-color cues (displayed in the same color used to find the target) captured attention and enhanced the processing of distractor letters appearing in that location. They also show that the ignored-color cue (the color not used to find the target) had no such effect relative to the neutral-color cue location.

The PE analyses supported the RT analyses. Overall, the effect of the location of the compatible distractor letter did not reach statistical significance, $F(2, 14) = 2.54$, $p = .1146$, $MSE = 0.0015$, $\eta_p^2 = .29$. However, planned comparisons showed that PE was significantly smaller when the compatible distractor letter appeared in the target-color cue location (.022) than when it appeared in the ignored-color cue location (.052) or in the neutral-color cue location (.041). There was no significant difference in PE between the ignored-color cue location and the neutral-color cue location.

ERP analyses. The ERP data were analyzed as a function of electrode laterality (contralateral vs. ipsilateral to the target location), target-color cue position (left hemifield vs. right hemifield), and target position (left hemifield vs. right hemifield). Each subcondition contained a total of 128 trials before trials that fell outside our RT cutoff or showed ocular artifacts were rejected. As described above, the ERP data analyses focused on two time windows: (a) the time window in which the target-color cue should produce an N2pc effect (200–300 ms after cue onset) and (b) the time window in which the target should produce an N2pc effect (400–500 ms after cue onset). Table 2 summarizes the ANOVA results.

Figure 6 shows the average waveforms for the electrodes contralateral and ipsilateral to the *target* (collapsed across the left and right target locations), as a function of whether the target-color cue and the target were in different visual hemifields or in the same visual hemifield (regardless of whether they were in the same exact location within that hemifield [valid conditions] or in adjacent locations [invalid/same-hemifield conditions]).

For the cue-elicited N2pc effect analyses (200–300 ms after cue onset), the ERP was more negative when the target-color cue was in the right hemifield (–3.817 μV) than when it was in the left hemifield (–3.123 μV). The three-way interaction between electrode laterality, target-color cue location, and target location was significant (see below for further data analyses on this interaction).

For the target-elicited N2pc effect analyses (400–500 ms after cue onset), the ERP was more negative for right targets (–2.339 μV) than for left targets (–1.767 μV). A normal target-elicited N2pc effect was also observed (the effect was –0.33 μV): The ERP was more negative for the contralateral electrode sites to the target location as compared with the ipsilateral sites. No other effects were found to be statistically significant for the cue- and target-elicited N2pc effect analyses.

The contingent capture hypothesis predicts that the N2pc effect should depend critically on whether the target-color cue and the target appear in the same hemifield (e.g., left cue and left target) or different hemifields (e.g., right cue and left target). Therefore, we conducted separate follow-up analyses for these two conditions, including only the factor of electrode laterality (contralateral or

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[5] In this data analysis, we averaged performance across the conditions in which the compatible distractor letter appeared in neutral locations that were ipsilateral and contralateral to the target location.

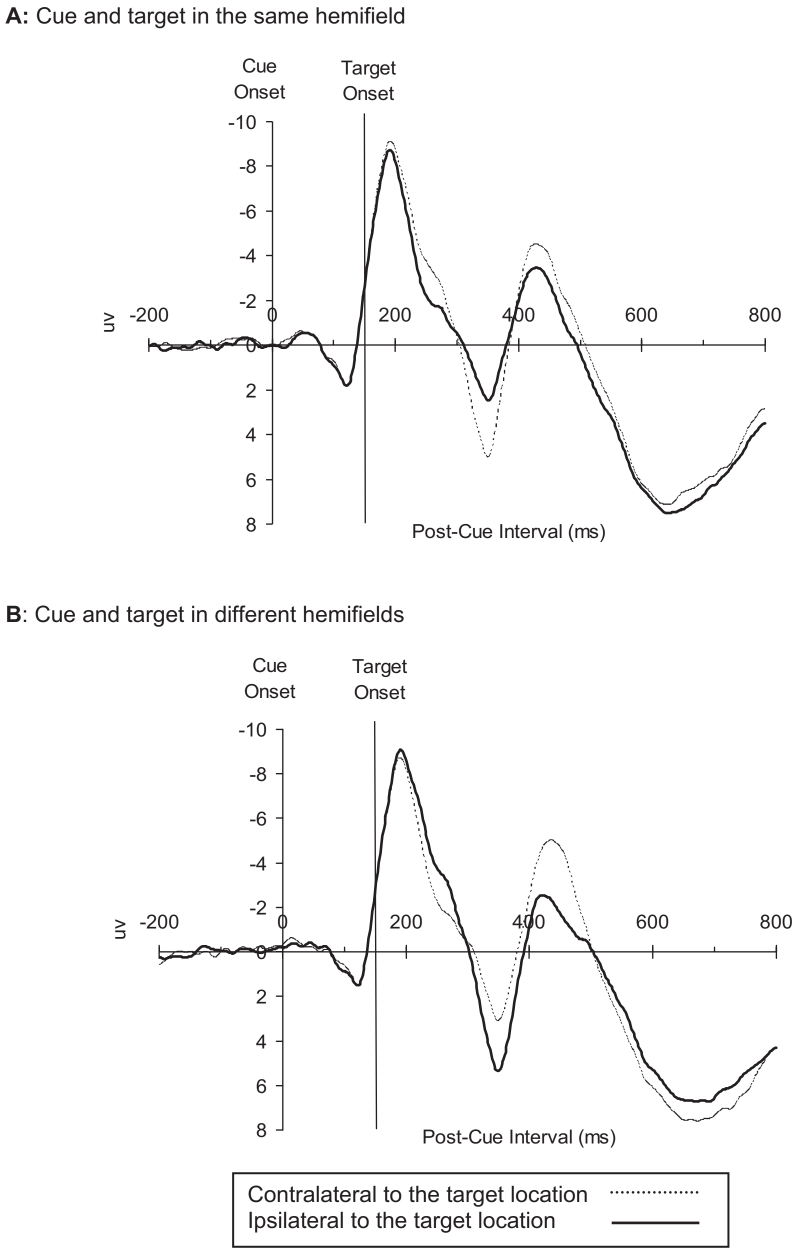


Figure 6. Grand average event-related brain potentials for target-color cues and targets, recorded and averaged across the posterior electrode sites contralateral or ipsilateral to the *target* location in Experiment 2. Panel A shows the average event-related brain potentials when the target-color cue and the target were in the same hemifield (regardless of whether the target-color cue was valid or invalid). Panel B shows the average event-related brain potentials when the target-color cue and the target were in opposite hemifields. Negative is plotted upward, and time zero represents color cue onset. The target onset (represented by a solid vertical line) was 150 ms after the color cue onset.

ipsilateral to the target location). The ANOVA results are summarized in Table 3.

Panel A of Figure 6 shows the results from the conditions in which the target-color cue and target were in the same visual hemifield. If the cue captures attention, it should produce an N2pc effect similar in polarity to that for the target. The data confirmed an N2pc effect to the cue during the 200–300-ms time window: The ERPs from electrodes contralateral to the cue/target were more negative than those of electrodes ipsilateral to the cue/target (the cue-elicited N2pc effect = –0.849 μV). There was also a trend toward a target-elicited N2pc effect (–0.922 μV), although the effect was only approached significance. We suspect that the trend is genuine given that it was significant in the essentially identical condition of Experiment 3 (see below for detailed discussion).

Table 3

Summary of ANOVAs on the ERPs in Experiment 2 as a Function of the Time Window (Cue-Elicited vs. Target-Elicited) and Whether the Target-Color Cue and the Target Were in the Same or Different Visual Hemifields

		200–300 ms (cue-elicited N2pc)			400–500 ms (target-elicited N2pc)		
Effect	*df*s	*F*	*MSE*	η_p^2	*F*	*MSE*	η_p^2
Electrode laterality (same hemifield condition)	1,7	11.91^{*}	0.243	.63	5.48	0.621	.44
Electrode laterality (different hemifield condition)	1,7	19.97^{**}	0.196	.74	34.56^{**}	0.350	.83

Note. ANOVAs = analyses of variance; ERPs = event-related potentials; N2pc = N2–posterior–contralateral effect.
$^{*}p < .05$. $^{**}p < .01$.

Panel B of Figure 6 shows the results from the conditions in which the target-color cue and target were in different visual hemifields. Note that for the sake of plotting the cue-elicited and target-elicited N2pc effect on the same graph, we must define the terms *contralateral* and *ipsilateral* with respect to either the cue or the target (but not both). We chose, somewhat arbitrarily, to define these terms with respect to the target (to be consistent with Experiment 1). Thus, if the cue captures attention, it should produce an N2pc effect opposite in polarity to that for the target. The data confirmed this prediction: The ERPs from electrodes contralateral to the target were less negative than those of electrodes ipsilateral to the target during the 200–300-ms time window (the cue-elicited N2pc effect = 0.988 μV) but were more negative during the 400–500-ms time window (the target-elicited N2pc effect = –1.739 μV).

Discussion

Experiment 2 used a spatial cuing paradigm to examine whether the cues containing the same color as the target would capture attention. Note that these cues were dots whereas the target was a letter and that the cue location was uncorrelated with the target location. Nevertheless, the behavioral data confirmed that they captured attention. First, as in previous cuing studies, RT was shorter when the target appeared in the target-color cue location than when it appeared in another location (a traditional cuing validity effect; e.g., Folk et al., 1992). This finding suggests that the target-color cue captured attention to its location and that a shift of attention was required when the target appeared in some other location. Note that the ignored-color cue (e.g., the red dots when the target was green) had no such effect. Thus, the cuing validity effects indicate that the colored cues capture attention only when they are drawn in the color used to find the target. In addition, RT was shorter and PE was smaller when the compatible distractor letter appeared at the target-color cue location than when it appeared at the ignored-color cue location or the neutral-color cue location. The deeper processing of the item in the target-color cue location provides further evidence of capture to that location (see also Remington et al., 2001).

In addition to the behavioral data, the ERP data provide further converging evidence for attentional capture by the target-color cue. The target-color cue produced a robust N2pc effect at posterior electrode sites during the interval 200–300 ms following cue onset. This electrophysiological evidence that attention moved to the target-color cue location refutes an alternative explanation of the cuing effect on RT, which states that the target-color cue does not actually capture attention but merely impedes the shift of attention to the target. In summary, these electrophysiological and behavioral findings indicate that irrelevant objects (i.e., cues) can elicit involuntary attentional capture when they share the property (e.g., a specific color) that is critical for finding the target. In fact, the N2pc effect in response to the cue was just as strong and rapid as that to the target, suggesting that the attentional system (initially) made no distinction between them.

It is worth noting that the target-elicited N2pc effect was smaller in magnitude, although not significantly so, $F(1, 7) = 3.85$, $p = .0907$, $MSE = 0.6933$, $\eta_p^2 = .35$, when the target-color cue and the target were in the same visual hemifield (half of the time in the exact same location) than when they were in different visual hemifields. One possible explanation is that when the target-color cue has already attracted attention to one visual field, a target subsequently appearing in that same visual field has less potential to produce any further shift of attention (presumably reducing the magnitude of the target-elicited N2pc effect). Also, note that following the N2pc effect to the target-color cue during the 200–300-ms time window there is a subsequent reversal in polarity (also see Luck & Hillyard, 1994, for a similar finding). If this reversal sometimes lingers beyond 400 ms postcue, it would undercut the N2pc effect triggered by the target (but only when the target-color cue and the target are in the same location).

The aforementioned reversal of the N2pc effect to the cue, which was also apparent in Experiment 2, deserves special mention (for a related effect, see Luck et al., 1994). One possible explanation for the reversal is that at some level, the attentional system realizes that the cued item is not the target and therefore attempts to compensate by shifting attention back to a more neutral state. This hypothesis naturally explains why the effect is stronger for the cue than for the target (for which no compensation is needed). Note, however, that it must be further assumed that the compensation is not completely successful or is not completed prior to the onset of the target display. Otherwise, we should not have seen evidence of faster responses when the target appeared in the same location as the target-color cue, and we should not have seen enhanced compatibility effects from distractor letters appearing at that location.

Because the target-color cue used in Experiment 2 was also a salient abrupt onset, one might argue that capture was due to pure salience rather than to a match with top-down control settings. Note, however, that the cue displays in this experiment always contained both red and green dots, in the opposite visual hemifields, among white dots. The critical effects were defined with respect to the dots that happened to have the color specified as being relevant by the instructions. Thus, pure stimulus salience would have resulted in capture either to all of the dots or to just the colored dots; in either case, there would have been no net pull of attention specifically toward the target-related color cue. Furthermore, Experiment 3 (described next) replicated these effects even though the color cues were not abrupt onsets. Thus, the cue-elicited N2pc effect obtained in our experiment was necessarily dependent on top-down attentional control settings and cannot be attributed to stimulus salience.

Experiment 3

Experiment 3 pitted color cues against abrupt onsets (i.e., contingent capture vs. capture by salience). The design was similar to that of Experiment 2 but with two important changes. First, we modified the color cues so that they were not themselves abrupt onsets: Instead of presenting the color cues as dots surrounding the box, we simply changed the color of the box frames (i.e., from white to red and from white to green). As in Experiment 2, there was one green cue and one red cue on every trial. Second, on half of the trials, we added a salient abrupt onset (four white dots surrounding only one of the boxes) to the cue display. This abrupt onset appeared simultaneously with the target-color cue and ignored-color cue (i.e., the change in color of the box frames) but never in the same location (see Figure 7).

If attention capture is entirely contingent on top-down control settings, the target-color cue should promptly capture attention regardless of whether there is a simultaneous abrupt onset in the cue display. Thus, the abrupt onset should have little influence on the cuing effect. Furthermore, target RT should be faster when the compatible distractor letter (e.g., the white letter *T* when the target is a red *T*) is presented at the target-color cue location as compared with other locations (including the abrupt onset location). On the other hand, if stimulus salience dominates contingent capture, then the abrupt onset might prevent the color cue from capturing attention. If so, the presence of an abrupt onset should greatly reduce or eliminate the cuing effect, the distractor compatible letter effect, and the color-cue elicited N2pc effect.

Another possibility is that the abrupt onsets will capture attention initially and thus delay capture by the color cue. Engagement and disengagement of attention by the abrupt onset might not influence RT to a target presented a few hundred milliseconds later (in our study, the target appeared 150 ms after the color cue). Even so, capture by the abrupt onset might still delay capture by a simultaneous color cue and thus noticeably delay the N2pc to the color cue.

Although one might wish to use the N2pc effect to the abrupt onset to determine whether it was attended, it is not possible to interpret such data meaningfully. With the color cues, there was a colored stimulus (red or green) on each side of the display, and the only distinction was which color was attended (counterbalanced across participants). There is no obvious way to use the same approach to isolate the attentional effects of the onsets. When there is an onset on one side of the visual field, that onset will inevitably produce lateralized brain activity (e.g., more activity in the contralateral hemisphere)—even if it was not attended. In other words, differential activity in the contralateral and ipsilateral electrode sites (i.e., the N2pc effect) with respect to the abrupt onset cannot be interpreted as an attentional effect.

Although we cannot directly assess attention capture by the abrupt onset using N2pc, we can still assess how the presence of an onset influences capture by the color cue (as described above). It is important to note that when we assessed the N2pc effect to the target-color cue for the onset condition, we averaged across trials with an abrupt onset on the same side as the color cue and trials with an abrupt onset on the other side. This procedure should help to cancel out any lateralized effect of the abrupt onset.

Method

Participants. There were 18 new participants, drawn from the same participant pool as in Experiments 1 and 2. Two participants were excluded owing to excessive HEOG activity (larger than ±3 μV). Thus, a total of 16 participants' data were included in the final data analyses. The increase in the total number of participants in this experiment relative to the previous experiments was due to the inclusion of more variables (e.g., onset vs. no-onset conditions); there are now fewer trials in each subcondition of the design, which would reduce the signal-to-noise ratio in those conditions. Figure 8 shows the average HEOG for the left-target and right-target trials for the remaining 16 participants. Half of the participants were instructed to respond to the red-colored letters and the other half to the green-colored letters.

Apparatus, stimuli, and procedure. Figure 7 shows an example of cue displays used in this experiment; in this example, the target is defined as the red object. The tasks, stimuli, and equipment were the same as in Experiment 2 except for the following. There were two cue display conditions: onset and no onset. The

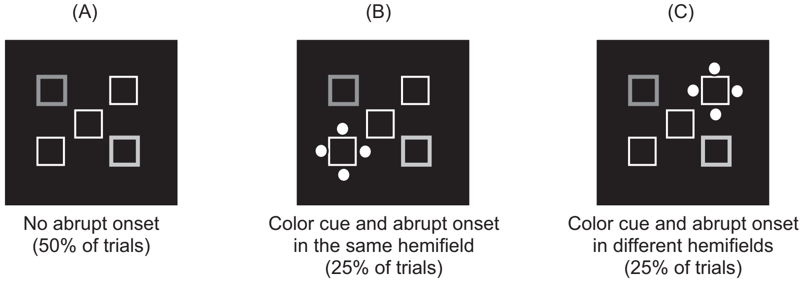


Figure 7. An example of the cue display for the red target letter used in Experiment 3. In this example of cue display, the top-left box was red and the bottom-right box was green in the real experiment. Half of the cue displays contained an abrupt onset (B and C) and half did not (A). Among the trials with an abrupt onset, the target-color cue and the abrupt onset were in the same hemifield on half of the trials (B) and were in different hemifields for the other half of the trials (C).

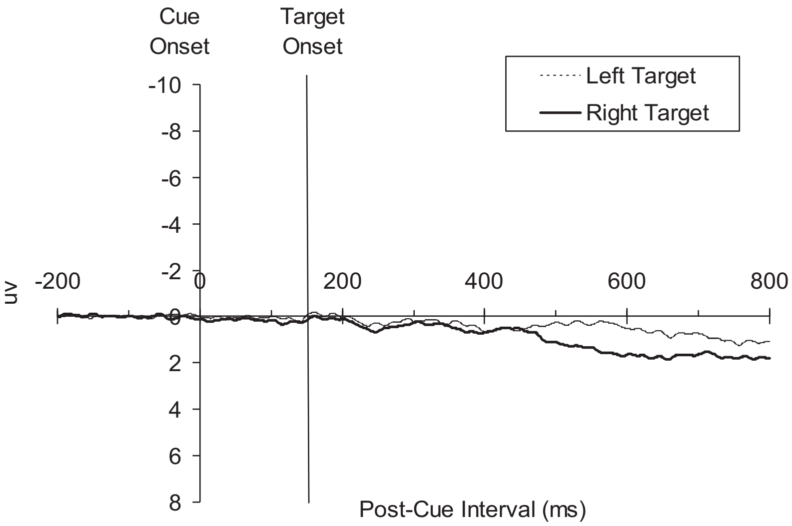


Figure 8. Grand average event-related brain potentials for the horizontal electrooculogram for the targets appearing in the left hemifield and targets appearing in the right hemifield in Experiment 3. Negative is plotted upward, and time zero represents color cue onset. The target onset (represented by a solid vertical line) was 150 ms after the color cue onset.

no-onset condition (50% of trials) was similar to that of Experiment 2. However, to minimize any abrupt onset of the color cue itself, we simply changed the color of the box frame (one box changed to green and one changed to red), rather than presenting colored dots. As in Experiment 2, the red and green color cues were always presented in opposite visual hemifields (left vs. right). The cue display in the onset condition (50% of trials) also contained the color cues but added an abrupt onset stimulus: White dots appeared around one of the four boxes at the same time that the boxes changed color. One constraint was that the salient, abrupt onset dots could never appear around one of the colored boxes (red or green). The onset stimulus was equally likely to be on the same side as the color cue as on the opposite side. Neither the color cues nor the abrupt onset reliably predicted the target location: All were 25% valid and 75% invalid.

Results

The data analysis was similar to that of Experiment 2. Application of the RT cutoffs eliminated approximately 0.11% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further eliminations of 12.5% of trials but no more than 25% of trials for any individual participant.

Behavioral data analyses: Cuing validity effects. Because target location and onset condition are not orthogonal factors, we conducted two separate data analyses: one for the onset condition and one for the no-onset condition. Data were again analyzed as a function of target location with respect to objects in the cue display. The target could appear in the target-color cue location, ignored-color cue location, and neutral-color cue location in the no-onset condition but could also appear in the onset location in the onset condition. Again, the ignored-color cue location refers to the location of the cue that was colored but not in the target color (e.g., the red box when the target was a green letter). Table 4 shows the mean RT and PE for each condition.

When the onset was absent (i.e., the no-onset condition), the results replicated those of Experiment 2. There was a main effect of target location on RT, $F(2, 30) = 70.19$, $p < .0001$, $MSE = 818$, $\eta_p^2 = .91$, and on PE, $F(2, 30) = 8.84$, $p < .001$, $MSE = 0.0009$, $\eta_p^2 = .35$. As in Experiment 2, planned comparisons showed that RT was shorter when the target appeared in the target-color cue location (500 ms) than when it appeared in the ignored-color cue location (551 ms) or the neutral-color cue location (548 ms). Thus, with respect to the target-color cue, there was a cue validity effect of 50 ms. Once again, however, there was no evidence of capture by the ignored-color cue. This finding suggests that the change in box color does not capture attention unless the new color happens to match the target color that the participants were looking for (contingent capture). Furthermore, planned comparisons on PE revealed that the only significant difference was that PE was higher when the target was in the neutral-color cue location (.039) than when it was in the target-color cue location (.020) or the ignored-color cue location (.031).

Table 4
Mean Response Times (RTs) in Milliseconds and Proportion of Errors (PEs) in Experiment 3 as a Function of Onset Condition and Target Location

Target location	RT	PE
No-onset condition		
Target-color cue location	500	.020
Ignored-color cue location	551	.031
Neutral-color cue location	548	.039
Onset condition		
Target-color cue location	504	.020
Ignored-color cue location	544	.027
Neutral-color cue location	560	.034
Onset location	560	.038

When the onset was present (i.e., the onset condition), there was a main effect of target location on RT, $F(3, 45) = 28.25$, $p < .0001$, $MSE = 4{,}327$, $\eta_p^2 = .67$, and on PE, $F(3, 45) = 3.93$, $p < .05$, $MSE = 0.0028$, $\eta_p^2 = .15$. Planned comparisons showed that RT was shorter when the target appeared in the target-color cue location (504 ms) than when it appeared in the other three locations (544 ms for the ignored-color cue location, 560 ms for the neutral-color cue location, and 560 ms for the onset location). Thus, with respect to the target-color cue, we observed an overall cuing validity effect of 51 ms. This effect size is nearly identical to that obtained with no abrupt onset (51 ms vs. 50 ms, respectively), consistent with the hypothesis that the presence of an abrupt onset has little or no impact on contingent capture by the target-color cue. It is important to note that RTs were not significantly different between the ignored-color cue location, neutral-color cue location, and onset location. Thus, there was no evidence that the abrupt onset captured attention. Planned comparisons on PE revealed that the only significant difference was that PE was higher when the target was in the onset location (.038) than when it was in the target-color cue location (.020).

Behavioral data analyses: Compatibility effects. To provide converging behavioral evidence for attentional capture by the target-color cue, we once again examined the effects of compatible and incompatible distractors appearing at the cued locations. Consistent with contingent capture, the distractor at the location of the target-color cue produced a compatibility effect on RT (25 ms), $F(1, 15) = 16.94$, $p < .001$, $MSE = 604$, $\eta_p^2 = .53$, and on PE (.013), $F(1, 15) = 16.33$, $p < .01$, $MSE = 0.0002$, $\eta_p^2 = .52$. However, as in Experiment 2, the distractor at the location of the ignored-color cue produced no such effect on RT or PE ($F\text{s} < 1.0$); the compatibility effect was 0.5 ms on RT and was .002 on PE.

To verify that these compatibility effects from the different types of color cues were significantly different, we performed a follow-up analysis. As in Experiment 2, we examined performance as a function of the location of the compatible distractor letter. We restricted this analysis to trials in which the onset was present (i.e., the onset condition) and the target appeared in the neutral cued location (i.e., where nothing happened in the cue display), so that all analyzed trials were invalid with respect to all possible cues. Thus, the compatible distractor letter could appear in the target-color cue location, ignored-color cue location, or onset location. If the target-color cue captures attention, then RT should be shorter when the compatible item is in the target-color cue location than when it is in other locations. However, if the onset captures attention, then RT should be shorter when the compatible distractor letter is in the onset location than when it is in other locations.

The overall effect of the location of the compatible distractor letter on RT was significant, $F(2, 30) = 10.09$, $p < .001$, $MSE = 3{,}418$, $\eta_p^2 = .78$. Planned comparisons showed that RT was significantly shorter when the compatible distractor letter appeared in the target-color cue location (535 ms) than when it appeared in the ignored-color cue location (558 ms) or in the onset location (572 ms). There was no significant difference between the ignored-color cue location and the onset location. No effects were significant on PE. These analyses indicate that the target-color cue captured attention but the abrupt onset did not.

ERP analyses. The ERP data were analyzed as a function of electrode laterality (contralateral or ipsilateral to the target location), onset condition (no onset, left hemifield, or right hemifield), target-color cue position (left hemifield or right hemifield), and target position (left hemifield or right hemifield). As described above, half of the trials contained an abrupt onset and half did not. Before trials that fell outside our RT cutoff or showed ocular artifacts were rejected, each of the no-onset subconditions contained a total of 64 trials and each of the onset subconditions contained 32 trials. As in Experiment 2, the data analyses focused on two time windows: (a) the time window in which the cue should produce an N2pc effect (200–300 ms after cue onset) and (b) the time window in which the target should produce an N2pc effect (400–500 ms after cue onset). The ANOVA results are summarized in Table 5.

For the cue-elicited N2pc effect analyses (200–300 ms after cue onset), the only significant effect in this data analysis was the three-way interaction between electrode laterality, target-color cue position, and target position (see below for detailed discussion on this interaction). No other effects were significant.

For the target-elicited N2pc effect analyses (400–500 ms after cue onset), the ERP was more negative when the onset was absent (−0.738 μV) than when it was in the left hemifield (−0.205 μV) or the right hemifield (−0.075 μV). The ERP was also more negative for a right target (−0.593 μV) than for a left target (−0.085 μV). Furthermore, an overall target-elicited N2pc effect of −1.148 μV was obtained: The ERP was negative for the electrode sites that were contralateral to the target location but was positive for the electrode sites that were ipsilateral to the target location. No other effects were significant.

The contingent capture hypothesis predicts that the N2pc effect should depend critically on whether the target-color cue and the target appear in the same hemifield (e.g., left cue and left target) or different hemifields (e.g., right cue and left target). Therefore, we conducted a follow-up analysis including only the factors of electrode laterality (contralateral or ipsilateral to the target location) and onset condition (absent or present collapsed across the left onset and the right onset). Figure 9 shows the average waveforms for the electrodes contralateral and ipsilateral to the target, as a function of whether there was an abrupt onset in the cue display and whether the target-color cue and the target were in the same or different visual hemifields. Table 6 summarizes the ANOVA results.

Panels A and B of Figure 9 show the results from the conditions in which the target-color cue and target were in the same visual hemifield, with and without a simultaneous abrupt onset. If the target-color cue captures attention, it should produce an N2pc effect similar in polarity to that for the target. The data analyses confirmed a cue-elicited N2pc effect (−0.578 μV) during the 200–300-ms time window. There was also a target-elicited N2pc effect (−0.944 μV) during the 400–500-ms time window. The overall ERPs were more negative without an abrupt onset than with an abrupt onset, both during 200–300 ms after cue onset (−1.430 μV vs. −0.854 μV, respectively) and during 400–500 ms after cue onset (−0.884 μV vs. 0.056 μV, respectively). Most important, the cue-elicited N2pc effect and the target-elicited N2pc effect did not differ significantly between the no-onset condition and the onset condition (see Figure 10, Panel A, for the N2pc effect obtained in both conditions). There was no evidence that the onsets influenced attentional capture by the color cues in this condition.

Table 5

Summary of Overall ANOVAs on the ERPs in Experiment 3 as a Function of Electrode Laterality (Contralateral or Ipsilateral to Target Location), Onset Condition (No Onset, Left Hemifield, or Right Hemifield), Target-Color Cue Position (Left or Right Hemifield), and Target Position (Left or Right Hemifield) for the Cue- and Target-Elicited N2pc Time Windows

		200–300 ms (cue-elicited N2pc)			400–500 ms (target-elicited N2pc)		
Effect	*df*s	*F*	*MSE*	η_p^2	*F*	*MSE*	η_p^2
Onset (O)	2,30	2.11	3.986	.12	5.65^{**}	2.802	.27
Electrode laterality (E)	1,15	< 1.0	0.228	.00	44.91^{**}	2.819	.75
Target-color cue position (C)	1,15	3.46	1.885	.19	< 1.0	3.678	.01
Target position (T)	1,15	< 1.0	0.785	.01	12.7^{**}	1.949	.46
O × E	2,30	< 1.0	0.220	.04	< 1.0	0.358	.05
O × C	2,30	< 1.0	1.395	.00	< 1.0	1.805	.05
E × C	1,15	3.13	0.211	.17	< 1.0	0.309	.06
O × T	2,30	< 1.0	1.276	.01	1.54	1.765	.09
E × T	1,15	< 1.0	29.058	.00	< 1.0	56.653	.03
C × T	1,15	< 1.0	0.993	.01	1.58	1.633	.10
O × E × C	2,30	< 1.0	0.165	.06	< 1.0	0.224	.04
O × E × T	2,30	2.71	1.050	.15	< 1.0	0.560	.01
O × C × T	2,30	1.86	0.643	.11	6.56^{**}	0.766	.30
E × C × T	1,15	20.54^{**}	1.545	.58	3.41	1.167	.19
O × E × C × T	2,30	< 1.0	0.193	.01	< 1.0	0.436	.04

Note. ANOVAs = analyses of variance; ERPs = event-related potentials; N2pc = N2–posterior–contralateral effect.
$^{**}p < .01$.

Panels C and D of Figure 9 show the results from the condition in which the target-color cue and target were in different visual hemifields. As in Experiment 2, we defined contralateral and ipsilateral electrode sites with respect to the visual field of the target. Therefore, if the target-color cue captures attention, it should produce an N2pc effect opposite in polarity to that for the target. The data confirmed this prediction: The ERPs from electrodes contralateral to the target were less negative than those of electrodes ipsilateral to the target during the 200–300-ms time window (the cue-elicited N2pc effect = 0.572 μV) but were more negative for the 400–500-ms time window (the target-elicited N2pc effect = –1.352 μV). Of note, neither the main effect of onset condition nor its interaction with the electrode laterality was significant in either time window (200–300 ms and 400–500 ms after cue onset). Thus, there was again no evidence that the onsets modulated attention capture by the color cues. Figure 10, Panel B, shows that the N2pc effects obtained with and without onsets are very similar. It remains possible, of course, that the onsets do have some small effect but that we were unable to detect it.

Discussion

In this experiment, we pitted the color cue against a simultaneous abrupt onset (on half of the trials). We presented the color cue by changing the color of one of the box frames from white to red and one from white to green, so that the color cues would not themselves be an abrupt onset.

In the condition with no simultaneous abrupt onset, the data replicated the findings of Experiment 2. We observed an enhanced compatibility effect when the distractor letter appeared in the location of the target-color cue. In addition, mean RT was shorter when the target appeared in the target-color cue location (500 ms) rather than in some other location (550 ms); this is the traditional cuing validity effect. This finding suggests that the target-color cue captured attention to its location. Note that the ignored-color cue (e.g., the red dots when the target was green) had no such effect. Thus, once again, the colored cues capture attention only when they are drawn in the color used to find the target.

The ERP data for the no-onset condition provide converging evidence for attentional capture by the color cue. As in Experiment 2, the target-color cue produced a robust N2pc effect at posterior electrode sites during the interval 200–300 ms following cue onset. These findings provide further evidence that irrelevant objects can elicit involuntary attentional capture when they contain features (e.g., color) related to the observer's top-down control settings.

The main question in the present experiment was whether the simultaneous presence of an abrupt onset elsewhere in the visual field would prevent the target-color cue from capturing attention. If so, one would expect to see the elimination of the target-color cuing effect. In contrast to this prediction, the target-color cuing validity effect was still strong despite the simultaneous presentation of the abrupt onset (504 ms for valid trials and 555 ms for invalid trials). The effect size was essentially identical to that obtained without an abrupt onset (51 ms vs. 50 ms, respectively).

The ERP data provide further evidence that the abrupt onset did not prevent attentional capture by color cue. We observed a cue-elicited N2pc effect at the 200–300-ms time window in the onset condition, and the magnitude was not reliably different from that in the no-onset condition. Thus, it appears that contingent capture occurred even when a color cue was presented simultaneously with a more salient event (an abrupt onset). One cannot rule out a modulation of the cue-elicited N2pc effect on the basis of a null result, but any such effect would appear to be relatively small.

One could propose that the abrupt onset captures attention involuntarily but later releases the attention to the color cue

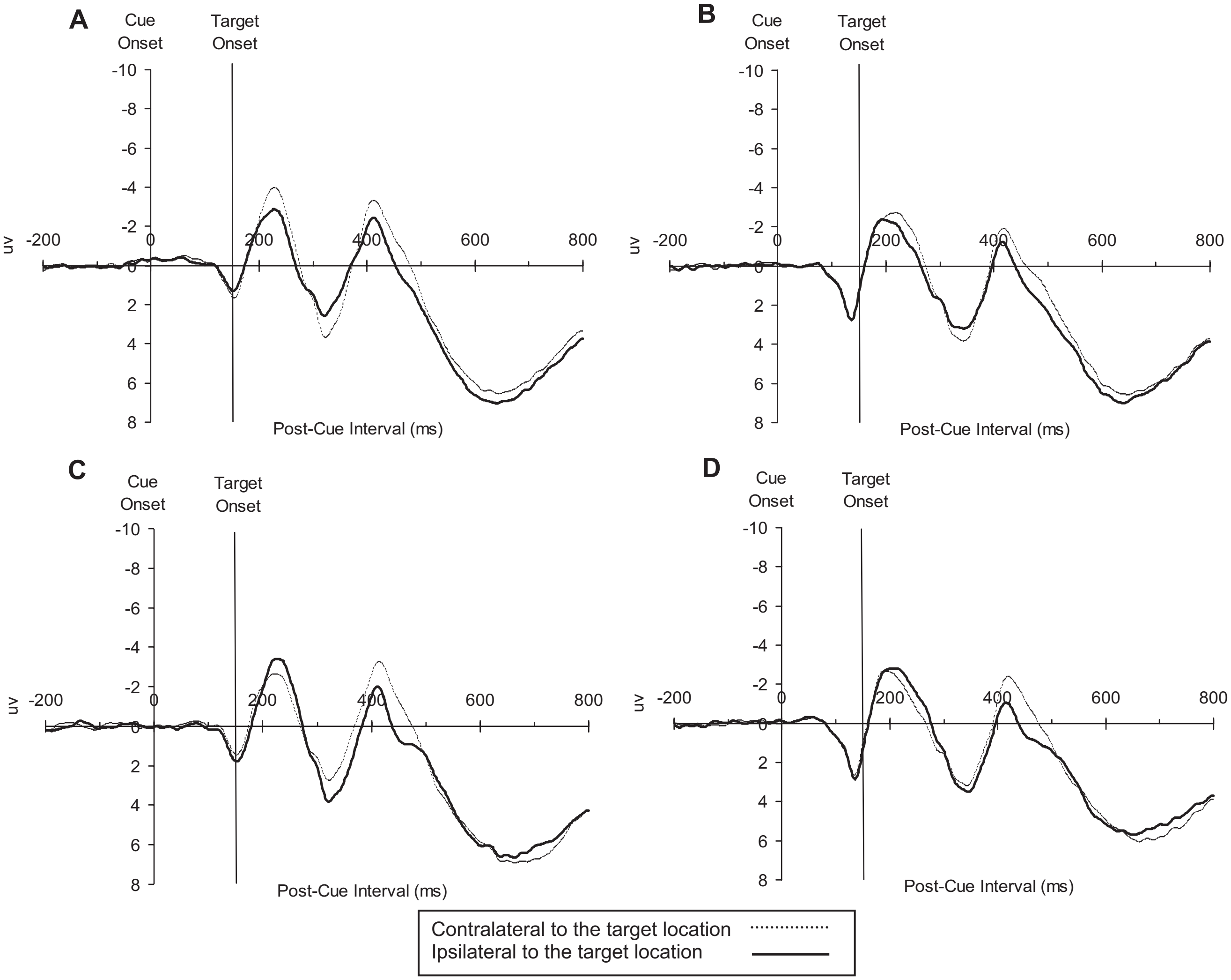


Figure 9. Grand average event-related brain potentials for color cues and targets as a function of onset condition (no onset vs. onset), recorded and averaged across the posterior electrode sites contralateral or ipsilateral to the *target* location in Experiment 3. The different panels show the average event-related potentials for the different conditions defined by whether there was an abrupt onset and whether the target-color cue and target were in the same or different hemifields. Panel A: No onset, same hemifield. Panel B: Onset, same hemifield. Panel C: No onset, different hemifield. Panel D: Onset, different hemifield. Note that for the onset conditions (Panels B and D), the data were collapsed across trials with an onset on the left and trials with an onset on the right. Negative is plotted upward, and time zero represents color cue onset. The target onset (represented by a solid vertical line) was 150 ms after the color cue onset.

location. On the basis of this hypothesis, one would expect to see a delay of the cue-elicited N2pc effect in the onset condition compared with the no-onset condition. No such delay was apparent. Figure 9 shows that the cue-elicited N2pc effect occurred approximately 200 ms after the color cue onset in both the onset and no-onset conditions. As a more formal test, we estimated N2pc onset using the baseline deviation approach (e.g., Osman, Bashore, Coles, Donchin, & Meyer, 1992). We conducted a series of *t* tests (one tailed, using participants as the random variable) on the cue-elicited N2pc data on a sliding 50-ms time window of 150 to 400 ms after the color cue onset (e.g., 150–200 ms, 160–210 ms, 170–220 ms). When five consecutive 50-ms time windows showed significant N2pc effects, the onset was defined as the beginning of the first such window. When the target-color cue and target were in the same hemifield, the estimated N2pc onset was 180 ms for both the onset and no-onset conditions. When the target-color cue and target were in different hemifields, the estimated N2pc onset was 190 ms in the no-onset condition and 180 ms in the onset condition. We also used Miller, Patterson, and Ulrich's (1998) jackknife method to examine whether the onset influenced time required to reach a threshold of 0.5 μV. We found no significant differences between the onset and no-onset conditions, regardless of whether the target and cue were in the same

Table 6

Summary of ANOVAs on the ERPs in Experiment 3 as a Function of Electrode Laterality (Contralateral or Ipsilateral to Target Location) and Onset Condition (No Onset vs. Onset Averaged Across Left and Right Hemifields) for the Cue- and Target-Elicited N2pc Time Windows When the Target-Color Cue and the Target Were in the Same or Different Visual Hemifields

		200–300 ms (cue-elicited N2pc)			400–500 ms (target-elicited N2pc)		
Effect	*df*s	*F*	*MSE*	η_p^2	*F*	*MSE*	η_p^2
		Target-color cue and target in same hemifield					
Onset (O)	1,15	4.47	1.189	.23	20.52**	0.689	.58
Electrode laterality (E)	1,15	19.79**	0.282	.57	34.39**	0.429	.70
O × E	1,15	< 1.0	0.060	.03	< 1.0	0.088	.03
		Target-color cue and target in different hemifields					
Onset (O)	1,15	1.01	0.969	.06	1.40	0.752	.09
Electrode laterality (E)	1,15	12.84**	0.382	.46	27.65**	1.104	.65
O × E	1,15	< 1.0	0.133	.02	< 1.0	0.360	.02

Note. ANOVAs = analyses of variance; ERPs = event-related potentials; N2pc = N2–posterior–contralateral effect.
** $p < .01$.

hemifield ($ps > .10$). In summary, there was no evidence that the onsets delayed or prevented capture by the target-color cue.

The preceding analyses concerned whether the onsets modulated capture by the target-color cues. One can also ask whether the abrupt onsets captured attention themselves. The ERP data cannot address this issue, as noted above, but the behavioral data can. One test is whether the onset produced a cuing validity effect. As shown in Table 2, mean RT was about the same regardless of whether the target appeared in the location of the abrupt onset (560 ms) or the location of the neutral-color cue (560 ms). It is important to note that the validity of the abrupt onset, with respect to the target location, was the same as the validity of the target-color cue (25% valid and 75% invalid). Thus, there was no more incentive for participants to move attention to the target-color cue than to the abrupt onset. The main difference between these types of stimuli is that the target-color cue matched the participant's top-down control settings, but the abrupt onset did not.

There was also no evidence that the onset enhanced compatibility effects from distractor letters subsequently appearing in that location. RT was not significantly shorter when the compatible distractor letter appeared in the onset location (572 ms) than when it appeared in the ignored-color cue location (558 ms). In fact, the trend went in the opposite direction. If genuine, this trend might reflect backward masking of the onset on the perception of the compatible distractor letter (see Luck, Hillyard, Mouloua, & Hawkins, 1996, for detailed discussion on this topic).

To summarize, several converging tests suggest that top-down control settings have a powerful influence over attentional capture and can largely prevent the capture of attention by an abrupt onset (see Lamy et al., 2003, for a similar argument). Likewise, there is no evidence that onsets capture attention or modulate the contingent capture of attention by a target-color cue.

General Discussion

Research by Yantis and Jonides (1984; see also Theeuwes, 1991, 1994) led to the hypothesis that abrupt onsets can capture attention involuntarily, at least when the target location is not known in advance (see Yantis & Jonides, 1990). Folk et al. (1992), however, provided evidence that attention capture is contingent on the observer's intentions (goal settings), not the salience of the object. The goal of the present study was to shed additional light on the contributions of stimulus salience and top-down control settings to involuntary attention capture. We addressed this issue using several converging tests, including traditional behavioral measures (RT and PE) and an electrophysiological indicator of attentional allocation (i.e., the N2pc effect).

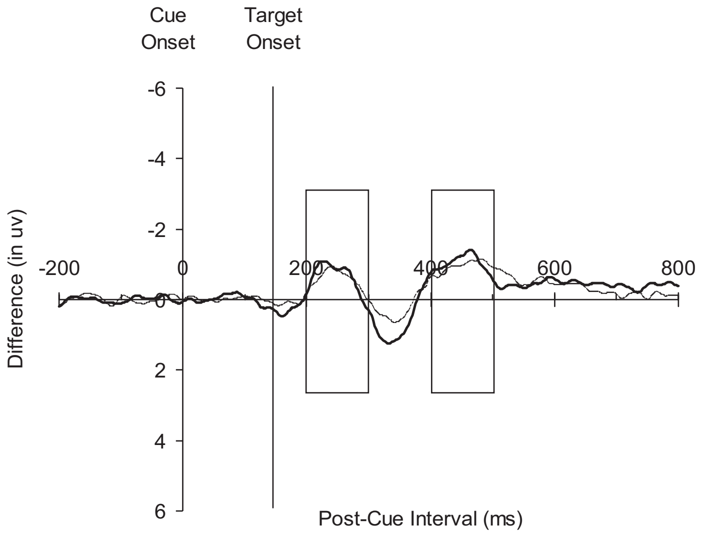
Converging Evidence for Contingent Capture

In the present study, participants searched for a target letter defined by its color (red for some participants, green for others). Experiment 1 confirmed that the target produced an N2pc effect occurring about 250–350 ms after target onset. Experiment 2 included a cue display, with one set of red dots and one set of green dots, to determine whether attention would be captured by the dots that have the color used to find the target. Even though there was little incentive for participants to allocate their attention to the cued location—cue location was uncorrelated with target location—the cue still captured attention. This capture was evidenced by a cuing effect (faster RT when the target appeared in the location of the color cue) and an enhanced compatibility effect for distractor letters appearing in the location where the target-color cue had recently appeared. More important, the target-color cue elicited a robust N2pc effect.

A critical feature of the present experiments is that overall, the displays used in the different conditions were identical; the only difference was which color was defined as the target color (counterbalanced across participants). Although one might argue that the colored stimuli (red and green) in the cue display were more salient than the white stimuli, any effect of such salience would have cancelled out. Thus, the attentional capture observed in these experiments was entirely contingent on a match between the physical properties of the cue and the physical properties used to find the target.

Experiment 3 pitted a color cue against a simultaneous abrupt onset in the cue display (i.e., pitted contingent capture against capture by salience). Rather than adding dots to the cue display (as

A: Cue and target in the same hemifield



B: Cue and target in different hemifields

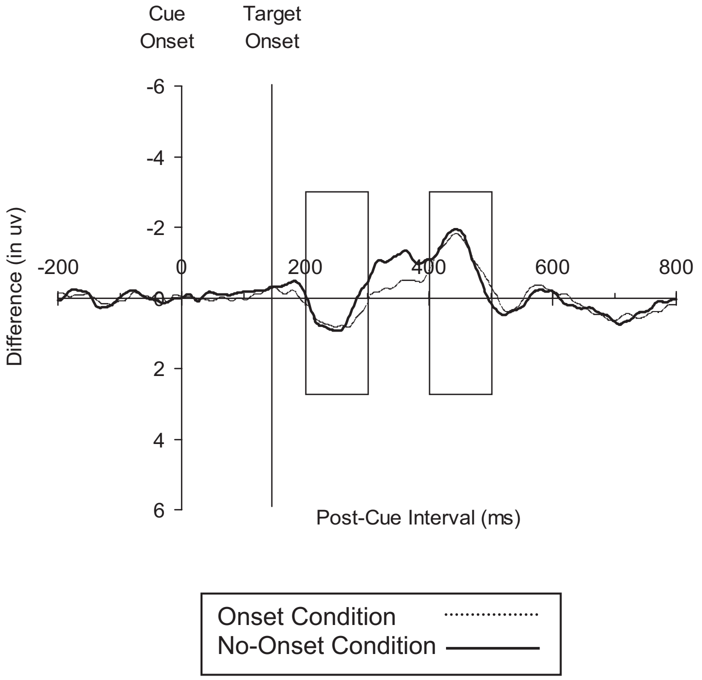


Figure 10. Grand average *difference* waveforms, calculated by subtracting activity in electrode sites ipsilateral to the target location from activity in electrode sites contralateral to the target location in Experiment 3. Panel A shows the differences obtained for the onset condition and the no-onset condition when the target-color cue and the target were in the same hemifield (regardless of whether the target-color cue was valid or invalid). Panel B shows the differences obtained for the onset condition and the no-onset condition when the target-color cue and the target were in opposite hemifields. Note that for the onset condition, the data were collapsed across trials with an onset on the left and trials with an onset on the right. Negative is plotted upward, and time zero represents color cue onset. The target onset (represented by a solid vertical line) was 150 ms after the color cue onset.

in Experiments 1 and 2), we turned one of the box frames from white to red and another from white to green, so that the color cue itself would not be an abrupt onset. On half of the trials, we added an abrupt onset—four white dots surrounding one of the noncolored boxes—to the cue display. If the abrupt onset (due to its greater salience) captures attention away from the target-color cue, then the target-color cue should no longer produce a cuing effect, enhance compatibility effects, or produce an N2pc effect. Contrary to this prediction, all three of these indices of attention capture were present and were similar for the onset and no-onset conditions. In summary, it appears that the color cue captured attention even when competing directly against an abrupt onset. There was also no evidence that the abrupt onset delayed attentional allocation to the color cue: The N2pc effect to the color cue began about 200 ms after color cue onset in both the onset and no-onset conditions (see Figure 9).

Not only did the abrupt onset not significantly modulate attention capture by the color cue, there was also no evidence that it captured attention itself. Although the N2pc effect to the abrupt onset cannot be used to infer attentional allocation (as noted in Experiment 3), the behavioral data do bear on this issue. We found no evidence of faster RT when the target appeared in the abrupt onset location. Furthermore, there was no evidence for enhanced processing of the compatible distractor letter (e.g., the distractor letter was *T* when the target was *T*) appearing in the abrupt onset location.

One might argue that the onsets used in Experiment 3 were too weak to capture attention. To rule out this alternative explanation, we conducted a behavioral version of this experiment in which participants might use onset as the property to find the target. We adopted the design from Experiment 3 with two modifications. First, we eliminated trials without an abrupt onset, because they are irrelevant for the present purposes. Second, the target display contained only one white letter. Thus, to find the target, participants might simply look for an abrupt onset. Results showed that the onset cue produced a significant cuing validity effect on RT of 15 ms, $F(1, 19) = 11.83$, $p < .01$, $MSE = 304$, $\eta_p^2 = .38$. This finding suggests that under an appropriate attentional control setting, onsets do have the power to capture spatial attention even with the simultaneous presence of the color cues.

Does Pure Salience-Based Attentional Capture Ever Occur?

Because we observed no evidence that abrupt onsets capture attention or disrupt attentional capture by the color cue, the present data support the extreme hypothesis that attentional capture by an object depends purely on the observer's intentions, not the abruptness of the onset. Nevertheless, it is possible that attentional capture by abrupt onsets (and other salient stimuli) sometimes occurs in the absence of a strong top-down set for specific stimulus features. Jonides and Yantis (1988), for instance, found that when a target was an abrupt onset there was no effect of the number of additional display items, even though participants had no motivation to search for onsets. They argued that in a neutral state of attentional readiness, attention can be captured involuntarily by abrupt onsets (see also Theeuwes & Burger, 1998; Yantis, 1993). Consider the example of driving to work. The sudden onset of the low-fuel warning light may capture your attention even though you are not set to look for that light (so long as you are not set to look for any other specific properties either). Thus, it remains possible that capture by certain salient stimuli is the default state, which can be overridden by strong top-down attentional control settings (see Folk, Remington, & Johnston, 1993).

A related position is suggested by the work of Bacon and Egeth (1994). They distinguished between singleton detection mode (i.e., searching for a unique object) and feature search mode (i.e., searching for a particular feature, such as red). They argued that with no strong incentive to adopt a set for a particular defining feature, participants adopt a general set to detect a salient discrepancy along any dimension. This singleton detection mode might correspond to the default setting proposed by Folk et al. (1993). Adopting singleton detection as a default control setting would prove advantageous when specific properties of unexpected events cannot be determined in advance.

Evidence for Attentional Capture by Stimulus Salience Other Than Abrupt Onsets?

Although we did not find evidence that abrupt onsets capture attention, a recent N2pc study by Hickey et al. (2006), discussed above, reported evidence for attentional capture by stimulus salience (a color singleton), independent from top-down control settings. Nevertheless, there are two concerns regarding Hickey et al.'s study. One concern is that their displays were not perfectly symmetrical (see Luck, 2005; Luck & Hillyard, 1994, for detailed discussion of this point). Accordingly, the observed N2pc effect might reflect differences in overall stimulus energy rather than attentional allocation. Hickey et al. acknowledged this problem, but they noted that the N2pc effect was not apparent in early latency ranges associated with sensory processing but was apparent in later latency ranges previously associated with attentional allocation.

A more serious concern with Hickey et al.'s (2006) study is that participants might have set themselves to search for any singleton, not just shape singletons (as instructed). As discussed above, this search mode is known as singleton detection mode (see, e.g., Bacon & Egeth, 1994; Lamy & Egeth, 2003; Leber & Egeth, 2006; but see Theeuwes, 2004). Although such a mode would result in sloppier attentional allocation as compared with searching specifically for shape singletons, it might produce more rapid attentional capture and require less effort to maintain. If participants were in singleton detection mode, then attentional capture by the color singleton could not be considered a genuine case of salience-based capture, independent of top-down control settings.

Relation to Other Studies

The major finding in the present study is that attentional capture by an object depended on the observer's intentions (i.e., top-down guidance) and not the abruptness of the onset (i.e., bottom-up salience). This finding is in line with the claim that attention allocation is guided by information held in working memory (e.g., Awh, Jonides, & Reuter-Lorenz, 1998; Downing, 2000; Soto, Heinke, Humphreys, & Blanco, 2005; Soto & Humphreys, 2006; Soto, Humphreys, & Heinke, 2006).

Soto et al. (2005), for instance, examined the effect of an item held in working memory on visual search performance (see Downing, 2000). Prior to each target display, participants were given a colored shape to memorize (called the cued object), such as a red square. The participants' other task was to identify a tilted line among vertical distractors in the target display. However, each line was also surrounded by an irrelevant colored shape that could match or mismatch the colored shape held in working memory. One key finding was that RT was shorter when the matching colored shape contained the target than when it did not. This result was not observed when participants were not required to maintain the cued object in memory. Furthermore, they found that the eyes tended to be captured by objects matching the cued object held in working memory, even when the location of the matching object always predicted the absence of the target (100% invalid). Soto et al. concluded that participants cannot help but, to some degree, search for an item that is currently held in working memory (see also Soto et al., 2006).

The present findings fit nicely with the evidence for attentional capture by objects matching the contents of working memory. The attentional control settings, held in working memory, determine which objects will capture attention and which will not. Salient objects will not necessarily capture attention if they do not match the current contents of working memory.

Conclusions

The present study used both traditional behavioral measures (RT and PE) and electrophysiological measures (the N2pc effect) to determine what factors contribute to involuntary attention capture. We argued that the N2pc effect is a promising tool for studying attentional capture because it provides a continuous indicator of attentional allocation and avoids many of the contaminants that cloud the interpretation of RT data. One contribution of this study is converging evidence that salience per se is not necessary for attentional capture. In our Experiments 2 and 3, two equivalently salient cues (red and green) were presented on each trial, yet several converging lines of evidence indicated that attention was captured by the cue that happened to have the same color as the target. Capture by the target-color cue (dots or a box) appeared to be just as strong and rapid as the allocation of attention to the target object itself (a letter). Furthermore, we found no evidence that contingent capture was diminished or delayed when the target-color cue competed for attention with a simultaneous abrupt onset. The picture that emerges from the present findings is that although capture is involuntary and stimulus triggered (bottom-up), it is nevertheless highly constrained by top-down control settings.

References

Atchley, P., Kramer, A. F., & Hillstrom, A. P. (2000). Contingent capture for onsets and offsets: Attentional set for perceptual transients. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 594–606.

Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 780–790.

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

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

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

Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science, 11,* 467–473.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433–458.

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology, 29,* 225–234.

Folk, C. L., & Remington, R. W. (1999). Can new objects override attentional control settings? *Perception & Psychophysics, 61,* 727–739.

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

Folk, C. L., Remington, R. W., & Johnston, J. C. (1993). Contingent attentional capture: A reply to Yantis (1993). *Journal of Experimental Psychology: Human Perception and Performance, 19,* 682–685.

Folk, C. L., Remington, R. W., & Wright, J. H. (1994). The structure of attentional control: Contingent attentional capture by apparent motion, abrupt onset, and color. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 317–329.

Gibson, B., & Amelio, J. (2000). Inhibition of return and attentional control settings. *Perception & Psychophysics, 62,* 496–504.

Gibson, B., & Kelsey, E. (1998). Stimulus-driven attentional capture is contingent on attentional set for display-wide visual features. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 699–706.

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

Jonides, J. (1981). Voluntary vs. automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention & performance IX* (pp. 187–203). Hillsdale, NJ: Erlbaum.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics, 43,* 346–354.

Kim, M. S., & Cave, K. R. (1999). Top-down and bottom-up attentional control: On the nature of the interference from a salient distractor. *Perception & Psychophysics, 61,* 1009–1023.

Lamy, D., & Egeth, H. E. (2003). Attentional capture in singleton-detection and feature-search modes. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 1003–1020.

Lamy, D., Tsal, Y., & Egeth, H. E. (2003). Does a salient distractor capture attention early in processing? *Psychonomic Bulletin & Review, 10,* 621–629.

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

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

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

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1000–1014.

Luck, S. J., Hillyard, S. A., Mouloua, M., & Hawkins, H. L. (1996). Mechanisms of visual-spatial attention: Resource allocation or uncertainty reduction? *Journal of Experimental Psychology: Human Perception and Performance, 22,* 725–737.

Luck, S. J., Hillyard, S. A., Mouloua, M., Woldorff, M. G., Clark, V. P., & Hawkins, H. L. (1994). Effects of spatial cuing on luminance detectability: Psychophysical and electrophysiological evidence for early selection. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 887–904.

Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology, 35,* 99–115.

Müller, H. J., & Rabbitt, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 315–330.

Osman, A. M., Bashore, T. R., Coles, M. G. H., Donchin, E., & Meyer, D. E. (1992). On the transmission of partial information: Inferences from movement-related brain potentials. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 217–232.

Pashler, H. (2001). Involuntary orienting to flashing distractors in delayed search? In C. L. Folk & B. Gibson (Eds.), *Attraction, distraction, and action: Multiple perspectives on attentional capture.* Amsterdam: Elsevier Science.

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

Prinzmetal, W., McCool, C., & Park, S. (2005). Attention: Reaction time and accuracy reveal different mechanisms. *Journal of Experimental Psychology: General, 134,* 73–92.

Remington, R. W., & Folk, C. L. (2001). A dissociation between attention and selection. *Psychological Science, 12,* 511–515.

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

Remington, R. W., Johnston, J. C., & Yantis, S. (1992). Involuntary attentional capture by abrupt onsets. *Perception & Psychophysics, 51,* 279–290.

Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-down guidance of attention from working memory. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 248–261.

Soto, D., & Humphreys, G. W. (2006). Seeing the content of the mind: Enhanced awareness through working memory in patients with visual extinction. *Proceedings of the National Academy of Sciences, USA, 103,* 4789–4792.

Soto, D., Humphreys, G. W., & Heinke, D. G. (2006). Working memory can guide pop-out search. *Vision Research, 46,* 1010–1018.

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

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

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

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

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

Theeuwes, J., & Burger, R. (1998). Attentional control during visual search: The effect of irrelevant singletons. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1342–1353.

Woodman, G. F., & Luck, S. J. (1999, August 26). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature, 400,* 867–869.

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

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 676–681.

Yantis, S., & Egeth, H. E. (1999). On the distinction between visual salience and stimulus-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 661–676.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 95–107.

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

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 121–134.

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