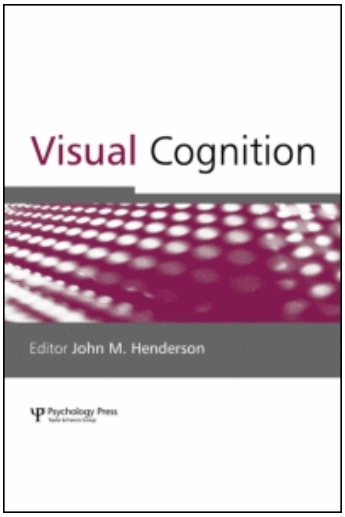

Visual Cognition
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713683696

Attentional capture by singletons is contingent on top-down control settings: Evidence from electrophysiological measures

Mei-Ching Lien [a]; Eric Ruthruff [b];Logan Cornett [a]
[a] Department of Psychology, Oregon State University, Corvallis, OR, USA [b] Department of Psychology, University of New Mexico, Albuquerque, NM, USA

First published on: 24 July 2009

To cite this Article Lien, Mei-Ching , Ruthruff, Eric andCornett, Logan(2010) 'Attentional capture by singletons is contingent on top-down control settings: Evidence from electrophysiological measures', Visual Cognition, 18: 5, 682 — 727, First published on: 24 July 2009 (iFirst)
To link to this Article: DOI: 10.1080/13506280903000040
URL: http://dx.doi.org/10.1080/13506280903000040

VISUAL COGNITION, 2010, 18 (5), 682–727

Psychology Press
Taylor & Francis Group

Attentional capture by singletons is contingent on top-down control settings: Evidence from electrophysiological measures

Mei-Ching Lien

Department of Psychology, Oregon State University, Corvallis, OR, USA

Eric Ruthruff

Department of Psychology, University of New Mexico, Albuquerque, NM, USA

Logan Cornett

Department of Psychology, Oregon State University, Corvallis, OR, USA

The present study examined whether the capture of spatial attention is driven by stimulus salience (e.g., object uniqueness) or by a match to current attentional control settings (contingent capture). We measured the N2pc effect, a component of the event-related brain potential thought to reflect lateralized attentional allocation. On every trial, a noninformative cue display containing a colour singleton box was followed by a target display of letters. Participants searched for a target letter in a specified colour (in Experiments 1–3) or within a specified shape (in Experiment 4) while ignoring other stimuli. The key manipulation was whether the singleton cue contained the target-defining feature (e.g., a specific colour). Experiment 1 revealed signs of attention capture—a cue validity effect and an N2pc effect—only for singleton cues that contained the target-defining feature. This pattern persisted even when we increased the salience of the singleton box (Experiments 2 and 3). Irrelevant colour singletons also failed to produce a significant N2pc effect when the target was defined based on shape rather than colour (Experiment 4). We conclude that attention capture is strongly contingent on top-down attentional control settings, not bottom-up stimulus salience.

Keywords: Attention capture; Spatial attention; Visual attention; N2pc effect.

Please address all correspondence to Mei-Ching Lien, Department of Psychology, Oregon State University, Corvallis, OR 97331-5303, USA. E-mail: mei.lien@oregonstate.edu

This research was supported by funding from the Oregon State University Research Office to M-CL and Oregon State University Undergraduate Research, Innovation, Scholarship & Creativity to LC.

http://www.psypress.com/viscog DOI: 10.1080/13506280903000040

The mind's eye, also known as *spatial attention*, can be voluntarily directed to the visual stimuli most relevant to our current goals, enabling us to take appropriate action. The involuntary capture of the mind's eye (stimulus driven) is also critical, because it enables rapid evaluation of important new stimuli (e.g., developing road hazards). This involuntary capture of attention has been found to occur very quickly, perhaps within 50 ms after the onset of an appropriate stimulus (see Lachter, Forster, & Ruthruff, 2004). In contrast, the voluntary allocation of attention has been found to be relatively slow, often taking more than 200 ms. Combined, these two modes of attentional control achieve a desirable compromise between striving towards current goals and responding rapidly to new opportunities or new dangers (see Bundesen, 1990; Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Yantis, 2000).

The present study examined the claim that involuntary attention capture is triggered by stimulus salience, regardless of the stimulus' relevance to current goals. One prominent type of salient stimulus is a *singleton*, an object that is different from a homogenous background on one dimension. A concrete example is a red car in a parking lot full of green cars. Even if this red car is completely irrelevant to the task at hand, it might nevertheless "stand out". Some studies have argued persuasively that such salient stimuli have the inherent power to capture spatial attention (e.g., Hickey, McDonald, & Theeuwes, 2006; Theeuwes, 1992, 1994), whereas others have argued that they do not (e.g., Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992). Because of the lack of consensus, the present study was designed to shed additional light on this issue. As will be discussed later, one potential problem with previous studies is that they relied on overt behavioural measures (e.g., response times), which typically afford several alternative explanations. To overcome this problem, we supplemented behavioural measures with electrophysiological measures that provide a moment-to-moment index of the deployment of visual attention. Our specific goal was to determine whether salient colour singletons involuntarily capture spatial attention, even when there is no incentive to look for such objects.

ATTENTIONAL CAPTURE BY STIMULUS SALIENCE

The earliest idea concerning attentional capture was that capture is driven by stimulus properties (for reviews, see e.g., Ruz & Lupiáñez, 2002; Yantis, 2000). A study by Yantis and Jonides (1984), for instance, demonstrated that abrupt onsets can capture attention involuntarily. In their study, one of the stimuli in each target display was an abrupt onset while others were revealed by removing line segments. The abrupt onset was irrelevant, in that it was no more likely to be the target than any other object. They found that when the

target was not an abrupt onset, response time (RT) increased substantially as the display size increased from two to four items. When the target was an abrupt onset, however, RT was relatively insensitive to display size. These findings suggest that the abrupt appearance of a new object triggered a shift of visual attention to that object, ensuring that it would be processed first. Later studies provided further evidence for this conclusion (see e.g., Jonides & Yantis, 1988; Müller & Rabbitt, 1989; Remington, Johnston, & Yantis, 1992; Yantis & Hillstrom, 1994; Yantis & Jonides, 1990).

Using a visual search paradigm, Theeuwes (1991, 1992, 1994) has provided evidence that other salient stimulus properties, such as singletons, capture attention even when they are task-irrelevant and capture would harm performance. Theeuwes (1994), for instance, had participants respond to the orientation of a line embedded within a particular circle. In the colour search condition, participants looked for a red circle among green circles; in the onset search condition, participants looked for the circle that had an abrupt onset. The critical manipulation was that, in half of the blocks of each search condition, the display contained an irrelevant singleton. In the colour search condition, one of the green distractors had an abrupt onset; in the onset search condition, one of the distractors was a colour singleton. In both conditions, the presence of an irrelevant singleton prolonged RT to the target. Theeuwes argued that even though participants were instructed to search for a specific kind of target, the presence of an irrelevant singleton captured attention initially, delaying the allocation of attention to the target.

Perhaps the most compelling evidence for the capture-by-stimulus-salience view comes from a recent electrophysiological study by Hickey et al. (2006). They confirmed that irrelevant singletons captured attention using a component of the event-related potential (ERP) called the *N2pc effect* (short for N2-posterior-contralateral). This component is an increased negativity over posterior scalp contralateral to an attended stimulus, peaking about 200–300 ms after the onset of that stimulus (see Luck, 2005, for a review). That is, the ERP at a given electrode in the left hemisphere becomes more negative when attention is directed to a right-hemifield stimulus (contralateral) than to a left-hemifield stimulus (ipsilateral), and vice versa. The N2pc effect, therefore, can be quantified as the average *difference* between contralateral and ipsilateral voltage.

Research indicates that the N2pc effect specifically reflects shifts of spatial attention, rather than eye movements or stimulus differences (e.g., Luck & Hillyard, 1990, 1994; Woodman & Luck, 2003; but see also Hickey, Di Lollo, & McDonald, 2009, for an alternative explanation). Thus, in contrast to the coarse information provided by behavioural measures such as RT, the N2pc effect is both a sensitive and specific measure of attention shifts (i.e., does not afford many alternative explanations). Furthermore, the N2pc effect can

provide both temporal (when) and spatial (where) information regarding an attentional shift.

Hickey et al. (2006) measured the N2pc effect in a visual search paradigm similar to that of Theeuwes (1991). Participants responded to the orientation of the line inside the unique shape (e.g., the diamond among nine circles), called the singleton target. On some trials, an irrelevant colour singleton appeared simultaneously with the shape singleton target. Hickey et al. found a small but significant N2pc effect to the irrelevant colour singleton when it appeared in the hemifield opposite the shape singleton target. They concluded that visual attention is directed to the target only after first being directed to the more salient, but task-irrelevant, colour singleton.

A CHALLENGE TO THE CAPTURE-BY-STIMULUS-SALIENCE VIEW

Although the findings just described suggest that singletons capture attention, it can be questioned whether this capture is driven entirely by stimulus salience. Folk et al. (1992) pointed out that, in many previous demonstrations of capture by salient stimuli, participants may have been actively looking for that kind of stimulus. Folk et al.'s *contingent capture hypothesis* proposes that attentional capture is involuntary—in the sense that the observer does not intend to attend the stimulus and cannot prevent capture—yet is contingent on top-down goal settings. That is, salient stimuli capture attention only when they possess properties that participants are looking for.

Folk et al. (1992) provided compelling evidence for their hypothesis in a paradigm with a cue display followed by a target display. There were four display locations and the cue validly indicated the target location only 25% of the time. Because the cue was uninformative, participants had no obvious incentive to attend it. Two types of cues (onset vs. colour) were combined with two types of targets (onset target vs. colour target). In the onset cue condition, white dots appeared abruptly around one of four peripheral boxes; in the colour cue condition, dots surrounded all of the peripheral boxes but one set of dots was coloured red instead of white. In the onset target condition, the target appeared abruptly in one of the boxes and nothing appeared inside the other boxes; it was assumed that participants would therefore learn to search for an onset. In the colour target condition, the target was the red object among white objects; it was assumed that participants would therefore learn to search for redness.

To the degree that a cue captures attention, RT should be faster when the cue validly indicates the target location than when it invalidly cues the target location (drawing attention to the wrong location). This phenomenon is

known as the *cue validity effect*. Folk et al. (1992) found that the onset cue produced a cue validity effect only in the onset target condition and the colour cue produced the effect only in the colour target condition. They argued, therefore, that onsets and colour singletons have no inherent power to capture attention involuntarily. Rather, only stimulus properties that match the current attentional control setting will produce involuntary capture (see also Arnott, Pratt, Shore, & Alain, 2001; Atchley, Kramer, & Hillstrom, 2000; Bacon & Egeth, 1994; Folk & Remington, 1999; Folk, Remington, & Wright, 1994; Gibson & Jiang, 1998; Gibson & Kelsey, 1998; Kiss, Jolicoeur, Dell'Acqua, & Eimer, 2008; Pashler, 2001).

The contingent capture hypothesis may provide a viable alternative explanation for many findings of capture by salient stimuli. In the case of Hickey et al. (2006), participants were asked to look for a shape singleton (e.g., a diamond among circles or vice versa). Although it is plausible that participants were specifically searching for a diamond or a circle, as instructed, it is also plausible that they adopted the simpler strategy of looking for *any* singleton object (known as *singleton-detection mode*; e.g., Bacon & Egeth, 1994; Lamy & Egeth, 2003). If participants were in fact searching for any singleton, then the irrelevant colour singleton may have captured attention only because it matched the current attentional control settings (i.e., looking for a singleton target). Hickey et al.'s study therefore neither unambiguously supports the capture-by-stimulus-salience view nor argues against the contingent capture hypothesis.

CRITICISMS OF THE EVIDENCE FOR CONTINGENT CAPTURE

Just as Hickey et al.'s (2006) study does not unambiguously support the capture-by-stimulus-salience view, Folk et al.'s (1992) study has been criticized on several grounds. Consider the absence of a cue validity effect for the onset cue in the colour target condition in Folk et al. Although this finding suggests that attention was not directed to the onset location when the target appeared, it is nevertheless possible that onsets cause an early shift of visual attention followed by a rapid redirection of attention away from the onset location (e.g., Kim & Cave, 1999; Theeuwes, Atchley, & Kramer, 2000). Although this hypothesis is difficult to rule out with behavioural measures, a few studies have provided arguments against it (e.g., Ansorge & Heumann, 2003; Ansorge & Horstmann, 2007; Ansorge, Horstmann, & Carbone, 2005; Folk & Remington, 1999, 2006; Lamy, Tsal, & Egeth, 2003; Remington, Folk, & McLean, 2001).

The controversy regarding the empirical support for the contingent capture hypothesis discussed previously highlights a drawback of the traditional behavioural measures of attentional capture (e.g., overall RT

and cue validity effects). Typically, they provide very indirect measures of attentional processes and therefore allow many alternative explanations. To overcome this problem, the present study relied upon electrophysiological measures, which provide a continuous measure of attentional shifts as they transpire. Whereas behavioural measures cannot easily detect capture by salient stimuli, followed by rapid disengagement, electrophysiological measures can detect this temporary shift while it happens. Electrophysiological measures are also very sensitive, often revealing evidence of deeper processing than was apparent in behavioural data (see Vogel, Luck, & Shapiro, 1998, for an excellent example). Therefore, when behavioural studies reveal no evidence for some process (e.g., a shift of attention), it is important to verify this finding with electrophysiological measures.

Using an electrophysiological approach, a recent study by Lien, Ruthruff, Goodin, and Remington (2008) provided converging evidence for the contingent capture view. In their Experiment 2, participants viewed a noninformative cue display containing a red box, a green box, and two white boxes. Participants were asked to search for a letter drawn in a specific colour (red or green) in the target display, which also contained one red, one green, and two white letters. It is important to note that the target display did not contain a colour singleton, so that participants would need to search for a specific colour. Under these conditions, Lien et al. found converging lines of evidence (substantial cue validity effects and N2pc effects) that attention was captured by the cue drawn in the target-defining colour. For instance, when the target letter was red, the red cue captured attention away from the green cue. Note that the cue was not a colour singleton and was no more salient than the other coloured item in the display. Critically, similar evidence for contingent capture was obtained even in Experiment 3, when the colour cue was pitted against a simultaneous abrupt onset.

Although Lien et al.'s (2008) Experiment 3 provides no evidence that abrupt onsets modulated capture by a stimulus drawn in the target-defining colour, it falls short of demonstrating that salient stimuli do not capture attention. They examined only one kind of salient stimulus—abrupt onsets. It is premature to conclude that other salient stimuli, such as colour singletons, do not capture attention involuntarily. Previous studies have, in fact, found different patterns of results with onsets and singletons (e.g., Belopolsky, Zwaan, Theeuwes, & Kramer, 2007). Furthermore, as noted above, Hickey et al. (2006) used the N2pc effect to argue that irrelevant colour singletons *do* capture spatial attention. Interestingly, it is even possible that they underestimated the amount of capture because, in their paradigm, the irrelevant colour singleton needed to compete for spatial attention with the simultaneous appearance of an actual target.

Even more importantly, Lien et al. (2008) may be consistent with attentional capture by the abrupt onset. Although they demonstrated

convincingly that the abrupt onset did not undermine contingent capture by a relevant stimulus, it is conceivable that both the relevant stimulus *and* the abrupt onset captured attention simultaneously. This ambiguity stems from the fact that it was not possible to meaningfully interpret the N2pc effect to the abrupt onset itself. Any such lateralized brain activity could reflect differences in stimulus energy rather than "attention" per se (Luck, 2005). Fortunately, the N2pc effect can be used to directly assess attentional capture by other kinds of salient objects, such as colour singletons, without the stimulus energy confound.

A recent study by Eimer and Kiss (2008) used the N2pc to assess capture by colour singletons. These authors found that colour singletons did produce an N2pc effect, indicating capture, when participants were looking for that colour. However, colour singletons did not produce an N2pc when the task was to look for an onset item, or to look for the smaller of several rectangles. Thus, their data contradict Hickey et al.'s (2006) findings and instead support contingent capture.

Eimer and Kiss (2008) do not offer a convincing explanation of why their data conflict with those of Hickey et al. (2006), beyond pointing out that they used a cueing paradigm whereas Hickey et al. did not. Both studies used tasks that could potentially be solved by looking for singletons, so strategy cannot necessarily explain the difference in findings. One limitation of Eimer and Kiss's study, which might possibly explain the discrepancy, is that their manipulation of singleton relevance was confounded with task type. As the authors themselves acknowledge, relevant singletons were combined with a colour search task, whereas irrelevant singletons were combined with an onset task or a size task. It is conceivable that the N2pc effect is reduced with the latter tasks, making it difficult to detect a modest amount of attentional capture by colour singletons. The experiments here solve this problem by comparing the effects of relevant and irrelevant singletons while holding the task type constant (Experiments 1–3). We will also replicate with a task based on shape (Experiment 4), as in Hickey et al. In addition, we will measure N2pc effects with a longer cue duration than that used by Eimer and Kiss (100 ms rather than 50 ms; see Experiment 2).

THE PRESENT STUDY

The present study aimed to determine whether a colour singleton can capture attention involuntarily, regardless of the top-down control settings. To provide a sensitive and specific measure of attentional capture, we used an electrophysiological approach (the N2pc effect, as in Hickey et al., 2006, and Eimer & Kiss, 2008). For the sake of completeness, we also reported behavioural measures (the cue validity effect, as in Folk et al., 1992). Instead

of presenting irrelevant singletons simultaneously with the target as in Hickey et al.'s study, we used a cueing paradigm in which the singleton cue display and target display are separated in time. This temporal isolation of the cue and target events helps to minimize overlap in the elicited N2pc effects and also enables us to measure cue validity effects in the behavioural data. Furthermore, it might actually be *easier* for an irrelevant colour singleton to capture attention in this paradigm, because the cue appears by itself, with no simultaneous competition for the capture of attention. Critically, whereas Hickey et al.'s (2006; see also Eimer & Kiss, 2008) participants may have used singleton-detection mode, we created a task in which participants clearly had no incentive to look for singletons in the target display (see later for more details).

The cue display contained a colour singleton amid several homogeneous background items (e.g., a red box among several green boxes). The colour singleton could be drawn in either the target colour or a nontarget colour. The target display, however, always contained one blue letter, one green letter, one red letter, and one white letter. All participants viewed the same displays (see Figure 1 for an example), but with different instructions regarding what to look for. In Experiments 1 and 2, one-third of participants responded to green letters, one-third responded to red letters, and one-third responded to blue letters. In Experiment 3, each participant performed three sessions, each with a different target colour. In Experiment 4, shape was the target-defining feature. In all experiments, however, the target was never a singleton and thus there was no incentive to use singleton-detection mode. Instead, participants had to rely on a specific top-down attentional setting (e.g., searching for a specific colour) to perform the task optimally.

Following Folk et al. (1992), we manipulated whether the singleton cues were valid or invalid. There were four possible target locations. On 25% of trials the colour singleton cue location was the same as the target location (the valid condition) and on 75% of trials the colour singleton cue location was different from the target location (the invalid condition). Thus, participants had no incentive to voluntarily shift attention to the colour singleton cue.

The main question was whether colour singletons have the power to capture spatial attention, even when they do not match top-down control settings. The competing theories make predictions for both the behavioural and electrophysiological measures. In the behavioural data, capture to the singleton cue location should result in a cue validity effect: Faster RT and lower proportion of errors (PE) when the singleton cue is in the same location as the upcoming target rather than a different location. In the electrophysiological data, capture of attention to the singleton cue location should produce an N2pc effect. Although our primary interest was in the singleton-elicited N2pc effects, we also examined the target-elicited N2pc

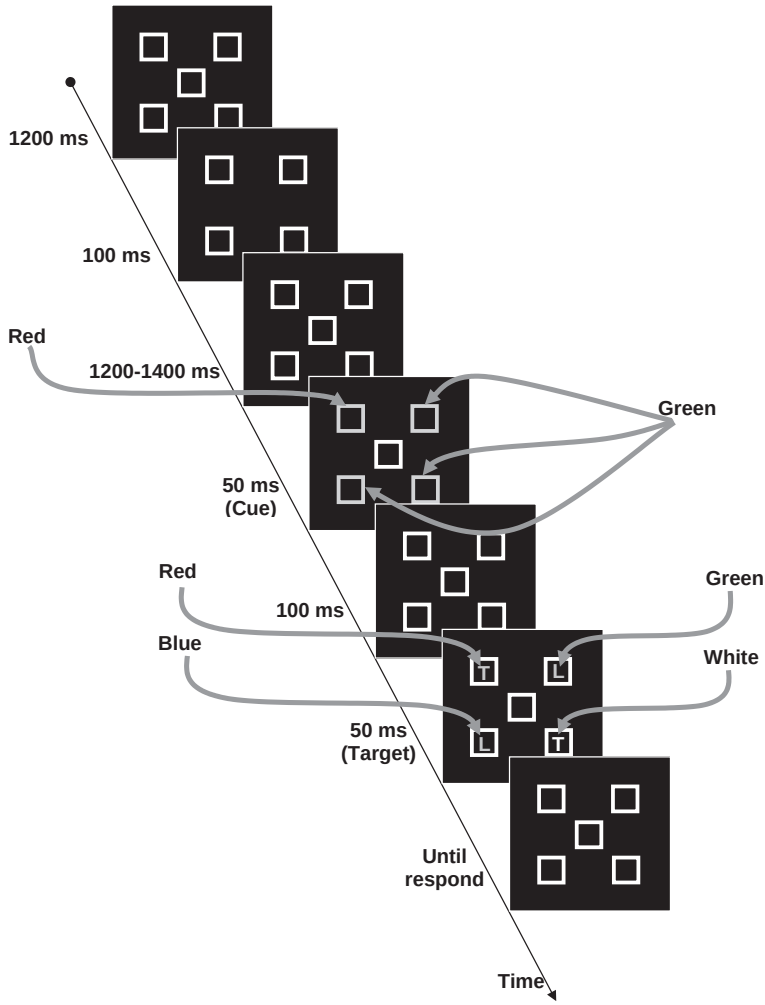

Figure 1. An example event sequence for the relevant singleton cue in Experiment 1. In the real experiment, the boxes in the cue display and letters in the target display were coloured. In this example, participants were instructed to respond to the red letter. In the cue display, the top-left box was red and the other boxes were green. In the target display, the top-left letter "T" was red, the bottom-left letter "L" was blue, the top-right letter "L" was green, and the bottom-right letter "T" was white.

effects for the sake of completeness. Within a trial, we define the N2pc effect with respect to the singleton cue location. Therefore, when the singleton cue and target are in the same hemifield, the singleton cue and target should produce an N2pc effect in the *same* direction. When the singleton cue and

target are in different hemifields, however, the polarity of the N2pc effect elicited by the target should be *opposite* to that of the singleton.

EXPERIMENT 1

Experiment 1 examined whether a colour singleton has the power to capture spatial attention, producing a cue validity effect and an N2pc effect, regardless of the top-down control settings. To create a condition where singleton-detection strategy was unlikely, we used target displays containing letters in four different colours (red, green, blue, and white). All participants received the same displays, but were given different instructions regarding which colour to respond to. Thus, a top-down control setting for a specific target colour was necessary to perform the task correctly. Singleton search would be pointless.

Method

Participants. Sixteen undergraduate students from Oregon State University participated in exchange for extra course credit. Data from four participants were excluded from the final data analyses due to excessive artefacts in the electroencephalographic data (see later). Therefore, data from 12 participants were included in the final data analyses. All reported having normal or corrected-to-normal acuity and normal colour vision.

Apparatus and stimuli. Stimuli, displayed on 19-inch ViewSonic monitors, were viewed from a distance of about 55 cm. Within each trial, three stimulus events were presented in succession (see Figure 1[1]): The fixation display, cue display, and target display. The fixation display consisted of five boxes: A centre box surrounded by four peripheral boxes (top-left, bottom-left, top-right, and bottom-right). Each peripheral box was equidistant from the centre box (7.66°, centre to centre) and from adjacent peripheral boxes (10.81°, centre to centre). Each box was 2.39 × 2.39°, drawn with thin (0.10°) white lines.

For the cue display, the four peripheral boxes changed colour, leaving one colour singleton and three identical-coloured background boxes (e.g., one red box and three green boxes). The target display consisted of the fixation display plus a letter (1.04° width × 1.35° length × 0.31° thick in Arial font) inside each of the four peripheral boxes. Each hemifield (left vs. right) contained one "T" and one "L". One letter was red (RGB values: 255, 10, 40), one was green (RGB values of 0, 125, 0), one was blue (RGB values of

[1] A coloured version of the event sequence is available at www.oregonstate.edu/~lienm/ACS.html

51, 51, 255), and the other was white (RGB values of 255, 255, 255). Among the 12 participants, 4 were instructed to respond to red letters, 4 to green letters, and 4 to blue letters.

Design and procedure. As shown in Figure 1, each trial started with the presentation of the fixation display for 1200 ms. Then, as a warning signal, the centre box was turned off for 100 ms and back on for 1200 ms to 1400 ms (determined randomly with a uniform distribution). The cue display then appeared for 50 ms and 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. The participants' task was to indicate whether the letter in the target colour was a "T" or an "L". Specifically, participants were to press the leftmost response-box button with their left-index finger for the letter "L" and the rightmost button with their right-index finger for the letter "T". After a response was recorded, the next trial began with the 1200 ms fixation display immediately.

We used three different colour-singleton cue conditions (see Figure 2), each occurring equally often for each participant. In the *relevant singleton condition*, the singleton had the target colour but the background boxes did not. For instance, the singleton cue could be target-defining colour red and the background boxes could be green in some trials and blue in others (as in the example shown in Figure 2A). In the *irrelevant singleton condition*, neither the singleton nor the background boxes had the target colour. In the case of a red target, for instance, the singleton cue could be green and the background boxes were blue in some trials but the assignment was reversed in other trials (Figure 2B). In the *competing singleton condition*, the singleton did not have the target colour, but the background boxes did. For instance, some trials might contain the blue for the singleton cue and the target-defining colour red for background boxes, whereas others contained the green for the singleton cue and the target-defining colour red for background boxes (Figure 2C). Thus, the nontarget-colour singleton was pitted against the three target-colour background boxes. These three singleton conditions were intermixed within blocks. Thus, each participant always saw two different colours for the peripheral boxes (one for the singleton cue and others for the background items) in the cue display. However, the assignment of specific colours (red, green, and blue) to the relevant, irrelevant, and neutral singletons in the cue display was counterbalanced across participants. Participants performed one practice block of 32 trials, followed by 18 experimental blocks of 64 trials each (a total of 1152 experimental trials).

The singleton cue and the target locations were randomly determined with the equal probability of occurring in each location. Thus, the location of the singleton cue could be the same as the location of the target for 25% of the trials (the valid condition). The remaining trials (75%) were invalid.

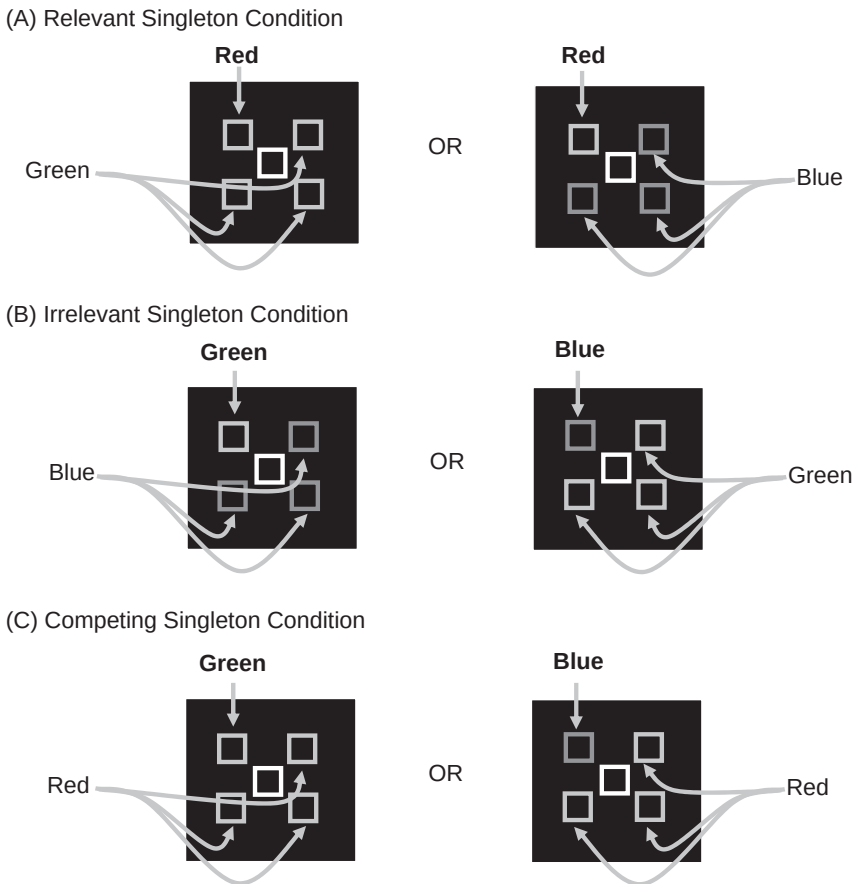

Figure 2. Example cue displays for the three singleton conditions of Experiment 1. In these example displays, the target colour is red.

Thus, the cue location did not predict the target location. Although this validity distinction is critical in the behavioural analyses to measure the cue validity effect, it is not critical for measuring the N2pc effect to the singleton cue location. The N2pc effect in response to the singleton cue can be assessed both for valid and invalid trials. The distinction crucial to the N2pc analyses is whether the singleton cue and target are in the same hemifield (50% of trials) or different hemifield (50% of trials).

EEG recording and analyses. The electroencephalographic (EEG) activity was recorded from F3, F4, C3, C4, T7, T8, P3, P4, P5, P6, PO5, PO6, O1, and O2. These sites and the right mastoid were recorded in relation to a

reference electrode at the left mastoid. The ERP waveforms were then re-referenced offline to the average of the left and right mastoids. The horizontal electrooculogram (HEOG) was recorded bipolarly from electrodes at the outer canthi of both eyes, and the vertical electrooculogram (VEOG) was recorded from electrodes above and below the midpoint of the left eye. Electrode impedance was kept below 5 kΩ. EEG, HEOG, and VEOG were amplified using Synamps2 (Neuroscan) with a gain of 2000 and a bandpass of 0.1–100 Hz. The amplified signals were digitized at 500 Hz.

Trials with artefacts were identified in two steps. First, trials with artefacts were rejected automatically using a threshold of $\pm$ 75μV for a 1000 ms epoch beginning 200 ms before singleton cue onset to 800 ms after singleton cue onset. Each of these candidate artefact trials were then inspected manually. Second, we computed average HEOG waveforms for the left-target and right-target trials, separately, to determine for each participant whether the eyes tended to move. Following Woodman and Luck (2003), we included in the data analyses only participants whose average HEOG activity was less than $\pm$ 3μV during the critical time windows (200–300 ms and 350–450 ms after singleton cue onset).[2] Four of the original 16 participants were eliminated because of artefact rejection on more than 25% of trials.

The critical question in our study is whether the colour singleton itself would capture attention and produce an N2pc effect. Data were analysed using the PO5 and PO6 electrodes only. To quantify the overall magnitude of the N2pc effect, we focused on the time window in which the colour singleton cue should produce an N2pc (200–300 ms after singleton cue onset). Specifically, the N2pc effect (i.e., the difference waveforms) was measured as the mean amplitude during this time window for the electrode site contralateral to the *singleton cue location* (e.g., the PO5 electrode when the singleton cue was in the right hemifield) minus the mean amplitude for

[2] A reasonable concern is that by eliminating trials with EEG artefacts (such as eye movements), we are actually eliminating the very trials on which attention was captured. Likewise, by eliminating participants with HEOG activity greater than 3μV in either direction, we are perhaps eliminating participants with the greatest amount of capture. To address this issue, we reanalysed the data without these exclusions. The results were indistinguishable from our original data with respect to the key dependent measures. Similar to the data reported in the main analyses, the cue validity effects for the irrelevant and competing singleton conditions were only 4 ms (*ns*) and −15 ms, $F(1, 15) = 13.91$, $p < .01$, respectively. Furthermore, the irrelevant singleton condition still showed no sign of an N2pc effect (the average effect was 0.153 μV), ts(15) ≤ 1.05, ps $\geq .3083$. The competing singleton condition still showed a reverse N2pc effect (the average effect was 0.787 μV), ts(15) ≥ 3.24, ps $< .01$. Similarly, Experiment 2 showed no cue validity effect for both irrelevant and competing singleton conditions (the effect was only 3 ms, Fs < 1). Most importantly, the irrelevant and competing singleton conditions still showed no sign of a singleton-elicited N2pc effect (−0.036 μV and 0.098 μV, respectively; ps $\geq .6234$). Thus, the absence of the capture by irrelevant singleton cues in our experiments was not due to the artefact rejection criteria we adopted.

the electrode site ipsilateral to the *singleton cue location* (e.g., the PO6 electrode when the singleton cue was in the right hemifield), relative to the mean amplitude during a 200 ms precue baseline period.

Although our primary interest was whether the singleton cue captures attention and produces an N2pc effect, we also examined the target-elicited N2pc effect. In these data analyses, we focused on the time window in which the target should produce an N2pc effect (350–450 ms after singleton cue onset, which translates to 200–300 ms after target onset). So that the analyses and numerical estimates of the N2pc effect would be consistent with the ERP figures, we continued to analyse the target-elicited N2pc effect with respect to the singleton cue location (rather than the location of the target itself). When the singleton cue and the target are in the same hemifield, the target-elicited N2pc effect should be in the same direction as the singleton-elicited N2pc effect. When they are in different hemifields, however, the target-elicited N2pc effect should have the opposite polarity to that of the singleton-elicited N2pc effect. We submitted the difference waveforms (the N2pc effect) to an analysis of variance (ANOVA), including same/different hemifield as an independent variable.

Results

In addition to excluding trials with EEG artefacts, we excluded trials from the final analyses of behavioural data (RT and PE) and ERP data if RT was less than 100 ms or greater than 2000 ms (0.11% of trials). Rejection of trials with EEG artefacts led to the further elimination of 13.58% of trials, with no more than 25% rejected for any individual participant.

Trials were also excluded from the RT and ERP analyses if the response was incorrect. An alpha level of .05 was used to ascertain statistical significance. Whenever appropriate, *p*-values were adjusted using the Greenhouse-Geisser epsilon correction for nonsphericity.

Behavioural data analyses

Although our experimental logic relies primarily on electrophysiological measures (reported later), we can also look for converging evidence in the behavioural data. Specifically, capture to the singleton cue location should result in a cue validity effect: Faster RT and/or lower PE when the singleton cue was in the same location as the upcoming target than when it was not. Accordingly, the data were analysed as a function of singleton condition (relevant, irrelevant, and competing) and cue validity (valid and invalid). Table 1 shows the mean RT and PE for each of these conditions.

The relevant singleton condition produced faster overall RT than the irrelevant and competing singleton conditions (RTs were 515, 523, and

TABLE 1
Mean response times (RT, in ms) and proportion of errors (PE) as a function of singleton condition (relevant, irrelevant, and competing) and cue validity condition (valid and invalid) in Experiment 1

	Cue validity condition		
Singleton condition	*Valid*	*Invalid*	*Cue validity effect*
RT			
Relevant	495 (12)	535 (11)	40 (6)
Irrelevant	520 (12)	526 (12)	6 (3)
Competing	539 (11)	514 (12)	−25 (3)
PE			
Relevant	.030 (.009)	.059 (.014)	.029 (.012)
Irrelevant	.041 (.011)	.047 (.011)	.006 (.004)
Competing	.060 (.019)	.044 (.011)	−.016 (.010)

The standard error of the mean is shown in parentheses.

527 ms, respectively), $F(2, 22) = 8.29$, $p < .01$, $\eta_p^2 = .43$. Also, a significant overall cue validity of 7 ms was obtained, $F(1, 11) = 22.23$, $p < .001$, $\eta_p^2 = .67$. Importantly, singleton condition interacted significantly with validity, $F(2, 22) = 44.06$, $p < .0001$, $\eta_p^2 = .80$. One could argue that this interaction stems from the opposite effects obtained between the relevant and competing singleton cue conditions. To verify differences between the relevant and irrelevant singleton cue conditions, we conducted an additional data analysis including only these two conditions. The interaction between singleton cue condition and validity was still significant, $F(1, 11) = 18.68$, $p < .01$, $\eta_p^2 = .63$.

Simple main effect analyses revealed a substantial cue validity effect (40 ms) in the relevant singleton condition, replicating previous studies, $F(1, 11) = 45.52$, $p < .001$, $\eta_p^2 = .81$. In contrast, the validity effect went in the opposite direction in the competing singleton condition (− 25 ms), $F(1, 11) = 73.25$, $p < .001$, $\eta_p^2 = .87$, suggesting that attention was captured not by the singleton (drawn in a to-be-ignored colour) but rather by the three identical background boxes (drawn in the target colour). The irrelevant singleton condition, where neither the singleton nor the background boxes had the target colour, produced a small, nonsignificant cue validity effect (6 ms), $F(1, 11) = 3.40$, $p = .0925$, $\eta_p^2 = .24$.

The PE data were generally consistent with the RT data. There was an overall cue validity effect on PE (.006), $F(1, 11) = 6.66$, $p < .05$, $\eta_p^2 = .36$. Although the main effect of singleton condition was not significant, $F(2, 22) = 1.33$, $p = .2837$, $\eta_p^2 = .11$, its interaction with validity was significant, $F(2, 22) = 3.94$, $p < .05$, $\eta_p^2 = .26$. The simple main effect analyses revealed that the cue validity effect was significant only for the relevant singleton condition (.029), $F(1, 11) = 5.63$, $p < .05$, $\eta_p^2 = .34$. The validity effect was

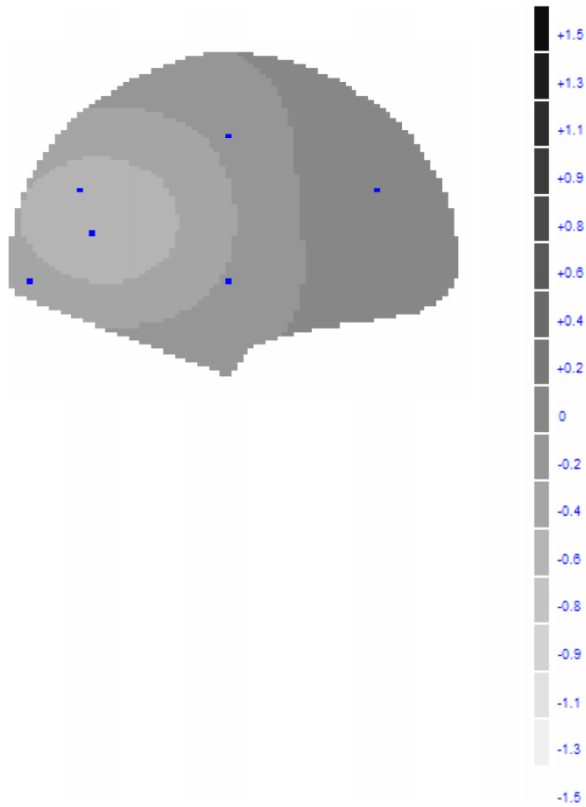

Figure 3. The scalp topography of the N2pc effect for the relevant singleton cue condition in Experiment 1, viewed from the right side of the brain (i.e., the front of the brain is on the right side of the figure) averaged across the left and right singleton cues. The time window used to assess the N2pc effect was 200–300 ms after singleton cue onset. The N2pc effect was strongest in the parietal and occipital lobes, consistent with previous research. A similar finding was obtained in Experiment 2. To view this figure in colour, please see the online issue of the Journal.

nonsignificant in the irrelevant (.006) and competing (−.016) singleton conditions.

ERP data analyses

Figure 3 shows the scalp topography of the N2pc effect during the time window 200–300 ms after singleton cue onset for the relevant singleton cue condition. Figure 4 shows the average waveforms for the contralateral and ipsilateral electrode sites, relative to the *singleton* cue location (collapsed across the left and right singleton cue locations). Figure 5 shows the difference waveforms (i.e., the N2pc effect) for the three singleton conditions. The

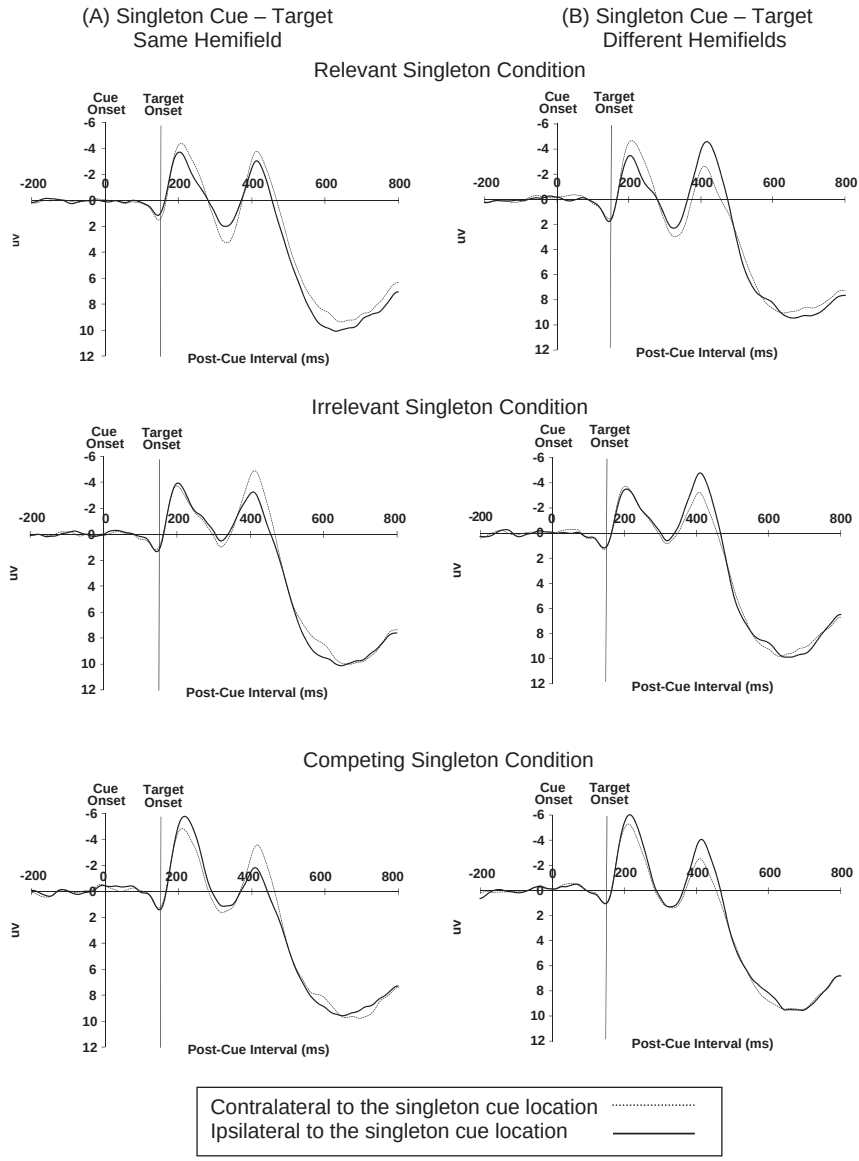

Figure 4. Grand average event-related brain potentials for singleton cues and targets in the three different singleton conditions (relevant, irrelevant, and competing), recorded and averaged across the posterior electrode sites contralateral (dashed line) or ipsilateral (solid line) to the *singleton cue location* in Experiment 1. (A) The average event-related brain potentials when the singleton cue and the target were in the same hemifield, for each singleton condition. (B) The average event-related brain potentials when the singleton cue and the target were in opposite hemifields, for each singleton condition. Negative is plotted upwards and time zero represents singleton cue onset. Target onset (represented by a solid vertical line) occurred 150 ms after singleton cue onset.

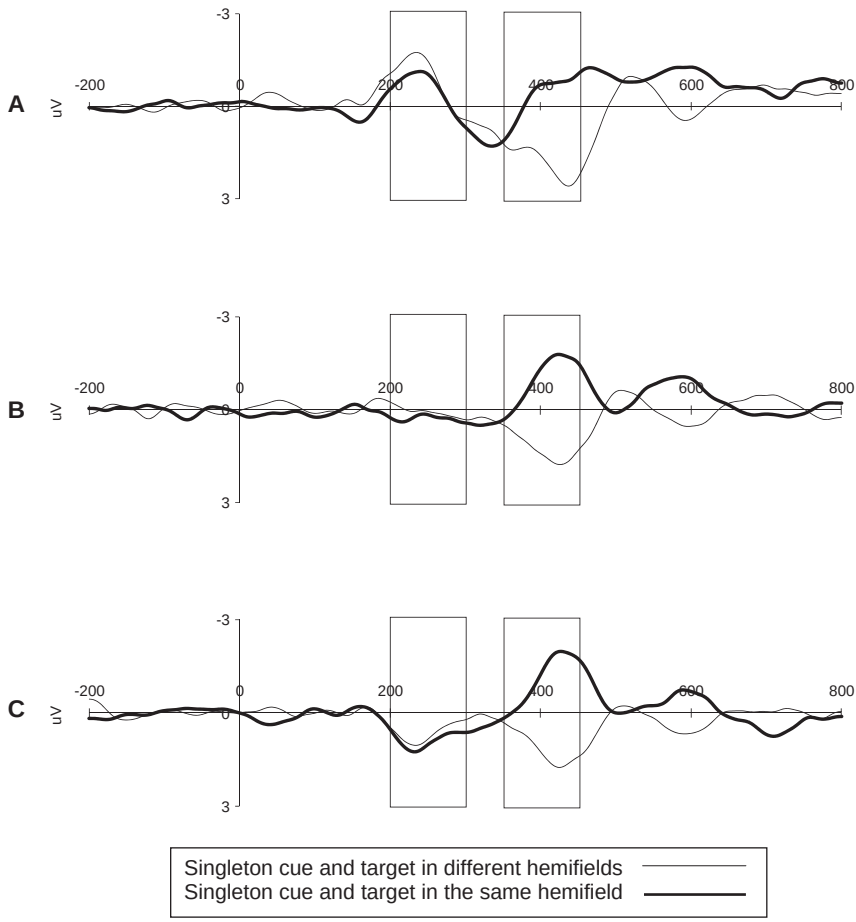

Figure 5. Grand average difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the singleton cue location from activity in electrode sites contralateral to the singleton cue location in Experiment 1. Data are plotted as a function of whether the singleton cue and the target were in the same hemifield or different hemifields for (A) the relevant singleton condition, (B) the irrelevant singleton condition, and (C) the competing singleton condition. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 200–300 ms after cue onset (for the singleton-elicited N2pc effect) and 350–450 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upwards and time zero represents singleton cue onset.

difference waveform data were analysed as a function of singleton condition (relevant, irrelevant, and competing), singleton-cue/target spatial relationship (same hemifield and different hemifields), and singleton cue location (left or right). We analysed the average value of the difference waveform over two different time windows: 200–300 ms after singleton cue onset (to assess the singleton-elicited N2pc effect) and 350–450 ms after singleton cue onset (to

assess the target-elicited N2pc effect). Each of the subconditions contained a total of 192 trials per participant before rejecting trials that fell outside our RT cutoff or showed ocular artefacts.

Singleton-elicited N2pc effects. Our primary aim was to determine whether different types of singleton cues capture attention and produce N2pc effects (indicated by negative values). Results for the time window 200–300 ms after singleton cue onset showed that only the main effect of singleton condition was significant, $F(2, 22) = 14.21$, $p < .0001$, $\eta_p^2 = .56$. The singleton-elicited N2pc effect was more negative for the relevant singleton condition (-0.736 μV) than for the irrelevant and competing singleton conditions (0.176 μV vs. 0.787 μV, respectively).

We conducted further two-tailed *t*-tests on the singleton-elicited N2pc effect averaged across left and right singleton cues for each singleton condition (one analysis for the same hemifield condition and one for the different hemifield condition). The relevant singleton cue produced a significant singleton-elicited N2pc effect both when it appeared in the same hemifield as the target (-0.570 μV), $t(11) = -2.22$, $p < .05$, and when it appeared in a different hemifield (-0.902 μV), $t(11) = -3.51$, $p < .01$. Although the competing singleton cue produced a significant singleton-elicited N2pc effect in both the same hemifield condition (0.906 μV), $t(11) = 4.58$, $p < .001$, and the different hemifield condition (0.667 μV), $t(11) = 2.67$, $p < .05$, the N2pc effect was reversed. This finding suggests that spatial attention was directed not to the singleton cue location but rather to the opposite visual hemifield, which contained a larger number of background boxes drawn in the relevant target colour (two vs. one). Most importantly, the irrelevant singleton cue failed to produce an N2pc effect. The trend actually went in the wrong direction and was not significant in either the same hemifield condition (0.284 μV) or the different hemifield condition (0.069 μV), $ts(11) \leq 1.83$, $ps \geq .0939$.

Target-elicited N2pc effects. The target-elicited N2pc data do not allow a test of our main hypothesis, but are included for the sake of completeness. Also note that, because we defined the N2pc effect with respect to the singleton cue location (for consistency with the N2pc figures), the direction of the target-elicited N2pc effect should depend critically on whether the singleton cue and target appeared in the same or different hemifield.

For the target-elicited N2pc effect analyses (350–450 ms postsingleton cue), as predicted, the target-elicited N2pc effect was negative when the target was in the same hemifield as the singleton cue (-0.809 μV) but was positive when the target was in the opposite hemifield (1.419 μV), $F(1, 11) = 57.77$, $p < .0001$, $\eta_p^2 = .84$. Although the interaction between singleton condition and singleton-cue/target spatial relationship was not significant, $F < 1.0$, the main effect of singleton condition was, $F(2, 22) = 6.06$, $p < .01$,

$\eta_p^2 = .36$. The average N2pc effect was more positive for the relevant condition (0.765 μV) than for the irrelevant and competing singleton conditions (0.125 μV vs. 0.025 μV, respectively). The interaction between singleton condition and singleton cue/target spatial relationship was not significant, $F < 1.0$.

We conducted further two-tailed t-test analyses on the target-elicited N2pc effects, averaged across left and right singleton cues, for each singleton condition (one analysis for the same hemifield condition and one for the different hemifield condition). In the relevant singleton condition, the target-elicited N2pc effect was in the predicted direction (− 0.302 μV), albeit not significant, when the target was in the same hemifield as the singleton cue, $t(11) = -1.06$, $p = .3140$. The target-elicited N2pc effect might be relatively small in the same hemifield condition because spatial attention had already been captured by the relevant singleton cue, and thus there was little need for a further shift of spatial attention in response to the target (see also Lien et al., 2008). When the target was in a different hemifield than the singleton cue, however, an especially large target-elicited N2pc effect in the opposite direction was obtained (1.833 μV), $t(11) = 8.03$, $p < .0001$. The exaggerated effect presumably occurs because the singleton cue previously captured attention to the opposite hemifield, thus requiring an especially large shift of attention back to the target location. This large magnitude disparity between the same and different hemifield conditions was not observed for the irrelevant singleton cue, providing further evidence that it did not reliably capture attention. Following an irrelevant singleton, there was a significant target-elicited N2pc effect in the same hemifield condition (− 1.032 μV), $t(11) = -5.49$, $p < .001$, and a reversed N2pc effect of a similar magnitude in the different hemifield condition (1.283 μV), $t(11) = 5.65$, $p < .001$. Following the competing singleton, there was a significant target-elicited N2pc effect in the same hemifield condition (− 1.092 μV), $t(11) = -6.27$, $p < .0001$, and a reversed N2pc effect of similar magnitude in the different hemifield condition (1.142 μV), $t(11) = 4.64$, $p < .0001$.

Discussion

Experiment 1 examined whether a colour singleton truly can capture attention, regardless of the top-down control settings. So that participants would clearly have no incentive to conduct a top-down search for colour singletons, we used a target display with four different colours (one red, one green, one blue, and one white).

Experiment 1 revealed several important findings. First, we found a substantial cue validity effect (40 ms) in the relevant singleton condition,

replicating previous findings that cues capture attention if they match top-down attentional control settings (e.g., Folk et al., 1992). In contrast, the validity effect went in the opposite direction in the competing singleton condition (– 25 ms), suggesting that attention was captured not by the singleton cue (drawn in a to-be-ignored colour) but rather by the three identical background boxes (drawn in the target colour). The irrelevant singleton condition, where neither the singleton nor the background boxes had the target colour, produced a small, nonsignificant cue validity effect (6 ms). A similar pattern was observed in the error data as well.

The ERP data agreed with the behavioural data. The singleton cue produced a robust N2pc effect (indicating attentional capture) during the interval 200–300 ms following singleton cue onset only when it is drawn in the task-relevant colour. In contrast, the singleton-elicited N2pc went in the opposite direction in the competing singleton condition. This finding suggests that the singleton cue lost the battle for attention with the background boxes drawn in the target-related colour. The singleton-elicited N2pc effect was negligible in the irrelevant singleton condition. Taken together, both the behavioural and electrophysiological findings indicate that singletons do not automatically elicit involuntary attentional capture unless they happen to contain the specific property that participants use to find the target.

EXPERIMENT 2

Experiment 2 was designed to examine whether the colour singleton can capture attention involuntarily when it is more salient. To make the singleton cue stand out better, we made three changes to the design of Experiment 1. First, we increased the number of peripheral boxes from four to eight. Second, we coloured the centre box in the same colour as the background boxes (instead of white, as in Experiment 1), to create a more homogenous background for the singleton to stand out against. Third, to make the singleton more perceptible, we doubled its duration (from 50 ms to 100 ms), as well as the duration of the target display (from 50 ms to 100 ms) and the cue–target interval (from 100 ms to 200 ms). Accordingly, the target appeared 300 ms after the singleton cue onset (rather than 150 ms after, as in Experiment 1). As a result, the time window for the target-elicited N2pc effect in the present experiment was 500–600 ms after the singleton cue onset, which still corresponds to 200–300 ms after target onset.

Although we attempted to make the colour singletons more salient, singletons still did not predict the target location (25% valid vs. 75% invalid). Therefore, participants still had no incentive to voluntarily shift attention to the singleton cue location. As in Experiment 1, the target displays was

identical for all participants and contained letters in four different colours (red, green, blue, and white). Thus, a search for a singleton would still not help participants to perform the task correctly.

Method

Participants. There were 20 new participants, drawn from the same participant pool as in Experiment 1. Five participants' data were excluded because either their averaged HEOG was larger than $\pm 3\mu V$ during the critical time windows (200–300 ms and 500–600 ms after the singleton cue onset) or their EEG artefact rejection was more than 25% of trials. Therefore, data from 15 participants were included in the final data analyses. All reported having normal or corrected-to-normal acuity and normal colour vision. As in Experiment 1, one-third of the participants were instructed to respond to the red letter, one-third to the green letter, and the other one-third to the blue letter.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except for the following changes. First, we added four peripheral boxes arranged directly above, below, left, and right of the centre box (Figure 6). They were the same size as the original four boxes and the same distance from the centre box. Based on the viewing distance of 55 cm, each peripheral box was equidistant from the centre box (7.66°, centre to centre) as in Experiment 1 and from adjacent peripheral boxes (6.53°, centre to centre).

The original four peripheral boxes remained in the same location as in Experiment 1. Participants were not informed that only these four locations could have contained the target. Second, in the cue display, we coloured the centre box the same colour as the background boxes. Third, we doubled the duration of the singleton cue display (from 50 ms to 100 ms), as well as the duration of the cue–target interval (from 100 ms to 200 ms) and the target display (from 50 ms to 100 ms). To facilitate direct comparison of results between experiments, we presented the four letters in the same four peripheral boxes as in Experiment 1 (i.e., targets never appeared inside the four new boxes).

Results

The data analysis was similar to that of Experiment 1. Application of the RT cutoffs eliminated 0.11% of the trials. Rejection of trials with EEG artefacts led to the further elimination of 9.52% of trials, but no more than 21% for any individual participant.

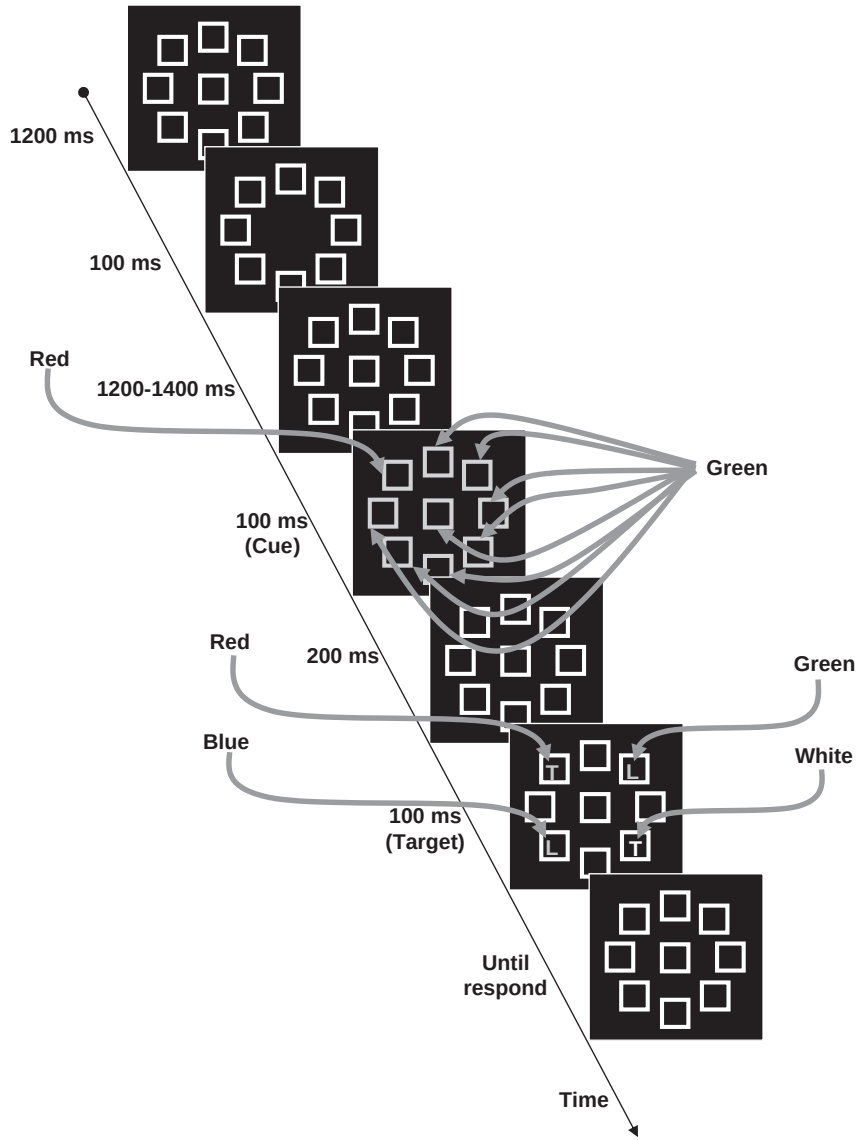

Figure 6. An example event sequence for the relevant singleton cue condition in Experiment 2. In the real experiment, only the boxes in the cue display and letters in the target display were coloured; others were white. In this example, participants were instructed to respond to the red letter. In the cue display, the top-left box was red, and the other boxes (including the centre box) were green. In the target display, the top-left letter "T" was red, the bottom-left letter "L" was blue, the top-right letter "L" was green, and the bottom-right letter "T" was white.

Behavioural data analyses

As in Experiment 1, the behavioural data were analysed as a function of singleton condition (relevant, irrelevant, and competing) and cue validity (valid and invalid). Table 2 shows the mean RT and PE for each of these conditions.

For the RT data, the overall cue validity effect approached significance, $F(1, 14) = 3.78$, $p = .0718$, $\eta_p^2 = .21$; mean RT was 8 ms slower in the invalid condition than in the valid condition. Although the effect of singleton condition was not significant, $F(2, 28) = 1.75$, $p = .1962$, $\eta_p^2 = .11$, it interacted with validity, $F(2, 28) = 16.25$, $p < .0001$, $\eta_p^2 = .54$. Simple main effect analyses revealed a significant cue validity effect (33 ms) in the relevant singleton condition, $F(1, 14) = 20.11$, $p < .001$, $\eta_p^2 = .59$. This effect was similar in magnitude to that obtained in Experiment 1 (40 ms). In contrast, the validity effect was negligible and went in the opposite direction in both the irrelevant singleton condition (− 6 ms) and the competing singleton condition (− 4 ms), Fs < 1.0.

The PE data were again consistent with the RT data. Mean PE was higher in the relevant and competing singleton conditions (.033 and .040, respectively) than in the irrelevant singleton condition (.028), $F(2, 28) = 6.47$, $p < .01$, $\eta_p^2 = .32$. As in the RT analyses, the interaction between singleton condition and cue validity was significant, $F(2, 28) = 3.56$, $p < .05$, $\eta_p^2 = .20$. Simple main effect analyses revealed that the cue validity effect approached significance for the relevant singleton condition (.011), $F(1, 14) = 4.32$, $p = .0565$, $\eta_p^2 = .24$, but was negligible in both the irrelevant

TABLE 2
Mean response times (RT, in ms) and proportion of errors (PE) as a function of singleton condition (relevant, irrelevant, and competing) and cue validity condition (valid and invalid) in Experiment 2

	Cue validity condition		
Singleton condition	*Valid*	*Invalid*	*Cue validity effect*
RT			
Relevant	528 (17)	561 (15)	33 (7)
Irrelevant	552 (18)	546 (14)	−6 (6)
Competing	547 (14)	543 (15)	−4 (4)
PE			
Relevant	.027 (.007)	.039 (.008)	.011 (.006)
Irrelevant	.026 (.007)	.029 (.006)	.004 (.004)
Competing	.045 (.010)	.044 (.006)	−.001 (.006)

The standard error of the mean is shown in parentheses.

singleton condition (.004), $F < 1.0$, and the competing singleton condition (−.001), $F(1, 14) = 2.76$, $p = .1187$, $\eta_p^2 = .16$.

ERP data analyses

Figure 7 shows the average waveforms for the contralateral and ipsilateral electrode sites, relative to the *singleton* cue location (collapsed across the left and right singleton cue locations). Figure 8 shows the average difference waveforms (i.e., the N2pc effect) for the three singleton conditions. The data analysis was similar to that of Experiment 1, except that the time window used to assess the target-elicited N2pc effect was 500–600 ms after the singleton cue onset (i.e., 200–300 ms after target onset).

Singleton-elicited N2pc effects. For the singleton-elicited N2pc analyses (200–300 ms after singleton cue onset), the N2pc effect was more negative in the relevant singleton condition (−0.686 μV) than in the irrelevant and competing singleton conditions (0.015 μV vs. 0.222 μV, respectively), $F(2, 28) = 5.67$, $p < .01$, $\eta_p^2 = .29$. These results are similar to those obtained in Experiment 1. No other effects were significant.

As in Experiment 1, we conducted further two-tailed *t*-test analyses on the singleton-elicited N2pc effect for each singleton condition. The relevant singleton cue elicited a significant singleton-elicited N2pc effect both when it appeared in the same hemifield as the target (−0.710 μV), $t(14) = -3.43$, $p < .01$, and when it appeared in a different hemifield (−0.662 μV), $t(14) = -2.54$, $p < .05$. The competing singleton cue tended to elicit a reversed N2pc effect (capture away from the singleton), although the effect failed to reach significance both when the singleton cue was in the same hemifield as the target (0.172 μV), $t(14) = 0.56$, $p = .5876$, and when it was in a different hemifield (0.273 μV), $t(14) = 1.14$, $p = .2727$. Nonetheless, Figure 8C shows a hint of a small, early singleton-elicited N2pc effect in the competing singleton condition. To examine this issue, we conducted additional analyses for this condition using the time window 140–240 ms after the singleton cue onset. The small trend was not statistically significant both when the singleton cue and the target were in the same hemifield, $t(14) = -0.25$, $p = .8047$, and when they were in different hemifields, $t(14) = 0.32$, $p = .7563$. Importantly, the irrelevant singleton cue failed to produce a substantial N2pc effect, both in the same hemifield condition (0.105 μV), $t(14) = 1.03$, $p = .3195$, and in the different hemifield condition, (−0.074 μV), $t(14) = -0.38$, $p = .7115$.

Target-elicited N2pc effects. As predicted, the overall target-elicited N2pc effect was negative when the target was in the same hemifield as the singleton cue (−1.154 μV) but was positive when the target was in the opposite hemifield as the singleton cue (0.752 μV), $F(1, 14) = 34.32$, $p < .0001$, $\eta_p^2 = .71$.

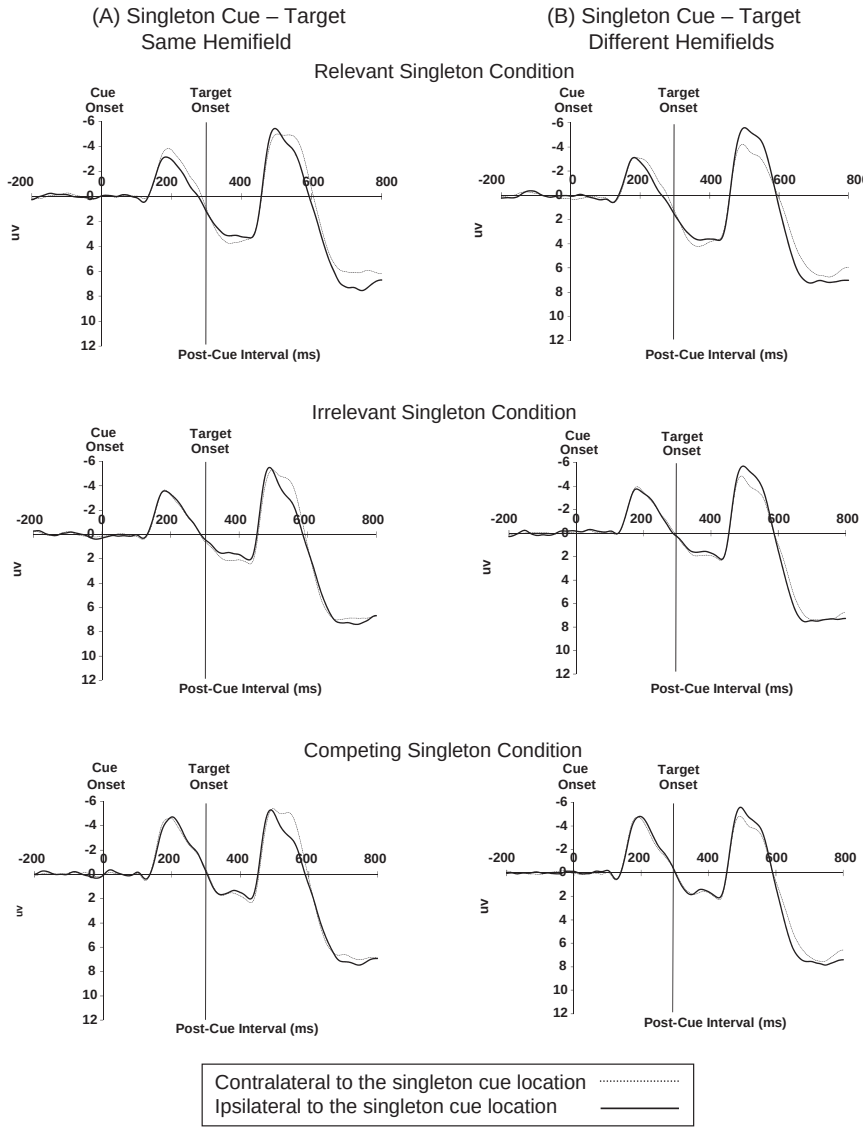

Figure 7. Grand average event-related brain potentials for singleton cues and targets in the three different singleton conditions (relevant, irrelevant, and competing), recorded and averaged across the posterior electrode sites contralateral (dashed line) or ipsilateral (solid line) to the singleton cue location in Experiment 2. (A) The average event-related brain potentials when the singleton cue and the target were in the same hemifield, for each singleton condition. (B) The average event-related brain potentials when the singleton cue and the target were in opposite hemifields, for each singleton condition. Negative is plotted upwards and time zero represents singleton cue onset. Target onset (represented by a solid vertical line) occurred 300 ms after singleton cue onset.

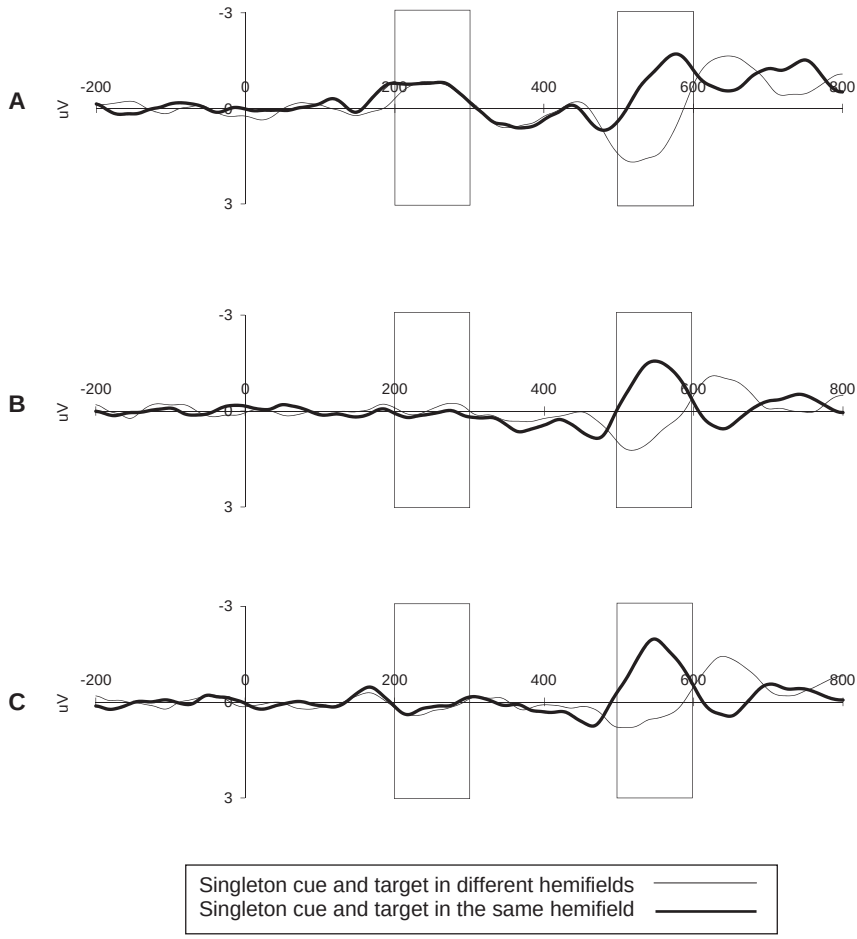

Figure 8. Grand average difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the singleton cue location from activity in electrode sites contralateral to the singleton cue location in Experiment 2. Data are plotted as a function of whether the singleton cue and the target were in the same hemifield or different hemifields for (A) the relevant singleton condition, (B) the irrelevant singleton condition, and (C) the competing singleton condition. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 200–300 ms after cue onset (for the singleton-elicited N2pc effect) and 500–600 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upwards and time zero represents singleton cue onset.

Because of the way we defined the N2pc effect (relative to the singleton cue location), these results simply indicate that the target letter captured attention to its location. No other effects were significant.

As in Experiment 1, we conducted further two-tailed *t*-test analyses on the target-elicited N2pc effect for each singleton condition. In the relevant

singleton condition, a substantial target-elicited N2pc effect was obtained when the target was in the same hemifield as the singleton cue (−1.023 μV), $t(14) = -3.76$, $p < .01$. The target-elicited N2pc effect was reversed when the target was in a different hemifield as the singleton cue (1.094 μV), $t(14) = 3.80$, $p < .01$. Unlike Experiment 1, the absolute value of the target-elicited N2pc effect was not noticeably smaller in the same hemifield condition; this might be because the longer cue–target onset interval (150 ms in Experiment 1 vs. 300 ms in Experiment 2) allowed more time prior to target onset for spatial attention to return to a neutral state. The competing singleton condition produced a substantial target-elicited N2pc effect in the same hemifield condition (−1.348 μV), $t(14) = -4.56$, $p < .001$, and a reversed, albeit not significant, N2pc effect in the different hemifield condition (0.463 μV), $t(14) = 1.78$, $p = .0966$. Similarly, the irrelevant singleton condition produced a substantial target-elicited N2pc effect in the same hemifield condition (−1.092 μV), $t(14) = -5.24$, $p < .0001$, but a reversed N2pc effect in the different hemifield condition (0.699 μV), $t(14) = 4.01$, $p < .01$.

Discussion

Experiment 2 was designed to increase the salience of the singleton cue and thus enhance its ability to capture attention. To do so, we doubled the duration of the singleton cue, increased the number of background boxes (from four to eight), and coloured the centre box the same colour as the background items. Thus, the singleton was the only item that had a particular colour, against eight background items all in the same colour. Despite these efforts, the results of Experiment 2 replicated those of Experiment 1. When the singleton was drawn in the relevant colour (used to find the target), it produced a significant cue validity effect and an N2pc effect (during the time window 200–300 ms after the singleton cue onset). When the singleton was drawn in an irrelevant colour, however, it failed to produce such effects. These results indicate that, in the absence of any incentive to explicitly search for singletons (singleton-detection mode), a colour singleton has no inherent power to capture attention.

One notable finding is that although the singleton-elicited N2pc effect in the competing singleton cue condition again was reversed (consistent with capture away from the singleton and towards the background boxes drawn in the relevant colour), it was nonsignificant and relatively small compared to that of Experiment 1 (see Figure 8C vs. Figure 5C), $F(1, 25) = 10.52$, $p < .01$, $\eta_p^2 = .30$. There is a simple explanation for this reduction. In Experiment 1 (where four peripheral boxes were used), there was only one background target-colour box in the visual hemifield containing the colour singleton cue and two background target-colour boxes in the opposite visual hemifield.

Thus, contingent capture would strongly pull attention away from the singleton cue (based on a 2-to-1 ratio of relevant colour in one hemifield vs. the other). In Experiment 2 (where eight peripheral boxes were used), however, there were three background target-colour boxes in the visual hemifield containing the colour singleton cue and four background target-colour boxes in the opposite visual hemifield. Thus, based on contingent capture, there should be relatively little net pull away from the hemifield containing the colour singleton cue. Another explanation for this reduction is that the centre box containing the target-defining colour in Experiment 2 (but not in Experiment 1) drew attention to its location and thus attenuates the capture by the peripheral boxes.

EXPERIMENT 3

Experiments 1 and 2 showed that irrelevant colour singletons did not strongly capture attention. The goal of Experiment 3 was to replicate the results of Experiments 1 and 2 with more power, so that we could detect even weak capture by irrelevant colour singletons. One change, therefore, was to include only the irrelevant singleton condition (focusing all of our data on the condition of primary interest). Another change was to have each participant respond to each possible target colour (red, blue, and green), in different blocks (i.e., a within-subjects manipulation). Participants responded to one target colour for seven consecutive blocks (one practice and six regular blocks) in one session, and then switched to another target colour for seven blocks, and so on. If attentional capture is contingent on top-down control settings, not bottom-up stimulus salience, we would still expect no capture by the irrelevant colour singleton, regardless of the target colour.

Method

Participants. There were 17 participants, drawn from the same participant pool as in previous experiments. None had participated in the previous experiments. Two participant's data were excluded because their EEG artefact rejection rate was more than 25%. Therefore, data from 15 participants were included in the final data analyses. All reported having normal or corrected-to-normal acuity and normal colour vision.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 2, with the exceptions noted later. Each participant received three sessions, each with a different target colour (red, green, or blue), in a single visit to the lab. Participants were informed the target colour prior to each session. The order of the three target colours was randomly determined for each participant. Each session contained one

practice block of 16 trials, followed by six regular blocks of 64 trials each. Only the irrelevant singleton condition was used. In addition to the breaks between blocks, participants were given a relatively long break between sessions.

Results

The data analysis was similar to that of Experiment 2. Application of the RT cutoffs eliminated 0.83% of the trials. Rejection of trials with EEG artefacts led to the further elimination of 5% of trials, but no more than 24% for any individual participant.

Behavioural data analyses

The behavioural data were analysed as a function of target colour (red, green, and blue), and cue validity (valid and invalid). Table 3 shows the mean RT and PE for each of these conditions. No effect was found to be significant in the RT and PE analyses. The cue validity effect was only − 1 ms on RT and .006 on PE.

ERP data analyses

Figure 9A and B show the average waveforms across the three target colours for the contralateral and ipsilateral electrode sites, relative to the *irrelevant singleton* cue location (collapsed across the left and right singleton cue locations), and Figure 9C shows the average difference waveforms (i.e.,

TABLE 3
Mean response times (RT, in ms) and proportion of errors (PE) as a function of target colour (red, green, and blue) and cue validity condition (valid and invalid) in Experiment 3

	Cue validity condition		
Target colour	*Valid*	*Invalid*	*Cue validity effect*
RT			
Red	551 (19)	554 (20)	3 (4)
Green	570 (16)	567 (18)	−3 (4)
Blue	554 (17)	552 (16)	−2 (3)
Average	558 (10)	557 (10)	−1 (3)
PE			
Red	.022 (.005)	.033 (.008)	.011 (.006)
Green	.035 (.010)	.037 (.006)	.002 (.006)
Blue	.026 (.007)	.031 (.006)	.005 (.004)
Average	.028 (.004)	.034 (.004)	.006 (.003)

The standard error of the mean is shown in parentheses.

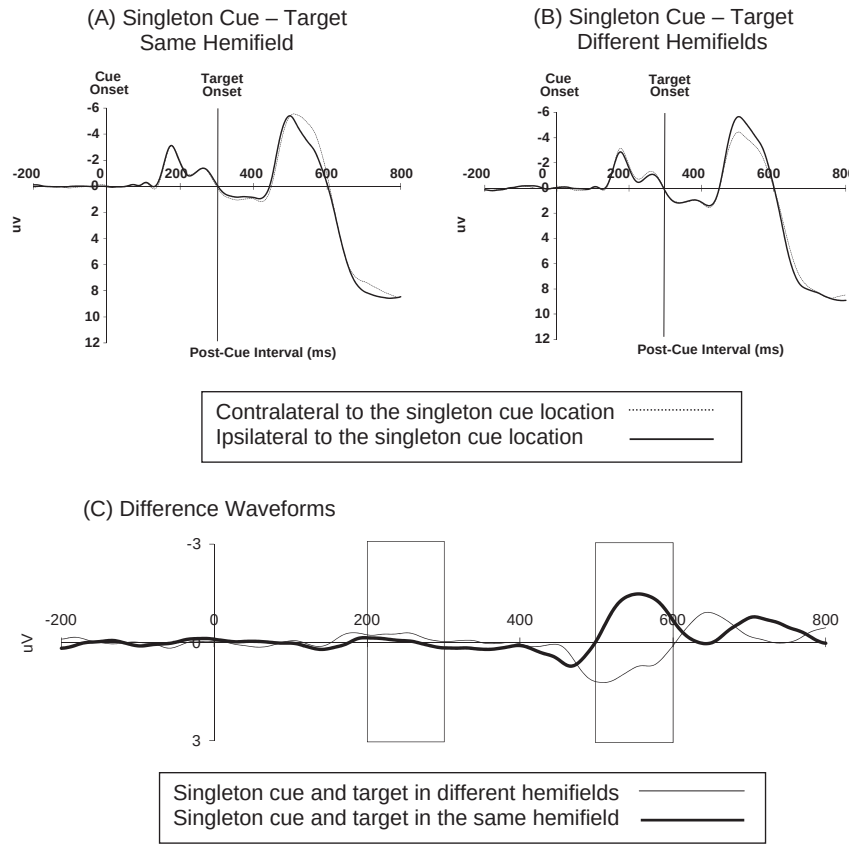

Figure 9. Grand average event-related brain potentials for singleton cues and targets recorded and averaged across the posterior electrode sites contralateral (dashed line) or ipsilateral (solid line) to the singleton cue location in Experiment 3. (A) The average event-related brain potentials when the irrelevant singleton cue and the target were in the same hemifield. (B) The average event-related brain potentials when the irrelevant singleton cue and the target were in opposite hemifields. Target onset (represented by a solid vertical line) occurred 300 ms after singleton cue onset. (C) Grand average difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the irrelevant singleton cue location from activity in electrode sites contralateral to the irrelevant singleton cue location as a function of whether the irrelevant singleton cue and the target were in the same hemifield or different hemifields. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 200–300 ms after cue onset (for the singleton-elicited N2pc effect) and 500–600 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upwards and time zero represents singleton cue onset.

the N2pc effect). We analysed the difference waveform as a function of target colour (red, green, and blue), singleton-cue/target spatial relationship (same hemifield and different hemifields), and singleton cue location (left or right)

over two different time windows: 200–300 ms after singleton cue onset (to assess the singleton-elicited N2pc effect) and 500–600 ms after singleton cue onset (to assess the target-elicited N2pc effect).

Singleton-elicited N2pc effects. The singleton-elicited N2pc analyses (200–300 ms after singleton cue onset) showed no significant effects. The overall singleton-elicited N2pc effect (200–300 ms after singleton cue onset) averaged across all target colours and conditions was only 0.0054, $t(14) = 0.03$, $p = .9789$.

Target-elicited N2pc effects. As predicted, the target-elicited N2pc analyses (500–600 ms after singleton cue onset) revealed that the overall target-elicited N2pc effect was negative when the target was in the same hemifield as the singleton cue (-0.966 μV) but was positive when the target was in the opposite hemifield as the singleton cue (0.886 μV), $F(1, 14) = 42.52$, $p < .0001$, $\eta_p^2 = .75$. As in previous experiments, these results simply indicate that the target captured attention to its location.

Discussion

Experiment 3 was designed to examine the generality of the findings in Experiments 1 and 2 using a within-subject instructional manipulation and using only the irrelevant singleton condition (to increase power). Even with more power, irrelevant colour singletons still produced no significant cue validity effect or N2pc effect. In summary, we again obtained little evidence for capture by the irrelevant colour singleton.

EXPERIMENT 4

In Experiments 1–3, irrelevant colour singletons did not appear to capture attention (unless they happened to have the property used to find the target). One can, however, question the generality of these findings. Because participants responded to one particular colour and ignored other colours, it is possible that participants actively inhibited the irrelevant colours. Because the target display always contained four different colours (red, green, blue, and white), inhibiting the irrelevant colours would have been a valuable strategy for finding the target colour. Perhaps capture by singletons is the norm, except when the singleton feature is inhibited because it directly competes with the target feature. Consistent with this possibility, Hickey et al. (2006) found evidence that colour singletons capture attention when participants were told to look for shape singletons (a different dimension). Experiment 4 was therefore designed to address this possibility. Specifically,

we examined whether irrelevant colour singletons would capture attention involuntarily when the target was defined along a different dimension, namely the shape dimension (as in Hickey et al., 2006).

To facilitate comparison between experiments, the exact same colour singleton cue conditions from Experiment 2 were used here, with the minor exception that coloured objects were circles rather than boxes.[3] As in Experiment 2, the centre circle was drawn in the same colour as the background circles. Note that all colour singletons are irrelevant when the defining target feature is a shape. Therefore, all of the colour singletons are now *irrelevant colour singletons*. In the target display, one circle was replaced with a diamond and one circle was replaced with a square, with these two shapes always located in opposite hemifields. Half of the participants were asked to respond to the letter within a diamond and the other to the letter within a square. These letters inside the shapes were always printed in white (the target display contained no colour other than white). The target displays were identical for all participants. Thus, a search for a singleton would again not help participants to perform the task correctly.

If the absence of capture by irrelevant colour singletons in Experiments 1–3 is due to the inhibition of features within the same dimension as the target-defining feature, this experiment should produce N2pc effects and cue validity effects for all colour singletons cues. But if capture is strongly contingent on top-down settings, then irrelevant colour singletons should still fail to capture attention.

Method

Participants. There were 28 participants, drawn from the same participant pool as in previous experiments. None had participated in the previous experiments. Four participants' data were excluded because their EEG artefact rejection rate was more than 25%. Therefore, data from 24 participants were included in the final data analyses. All reported having normal or corrected-to-normal acuity and normal colour vision.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 2, with the exceptions noted later. First, we changed the boxes to circles, while keeping the colours of the items the same as in Experiment 2. Each circle was 2.39° in diameter, which was the same visual angle as the boxes used in the previous experiments. As in Experiment

[3] We wanted to use diamonds and squares as targets, since they are well-matched, differing only in orientation. This meant that we could no longer use squares in the fixation and cue displays. So we replaced the squares with circles, against which the diamond and square targets were roughly equally easy to discriminate.

2, three different types of colour singleton cues were intermixed within blocks. Because they were all unrelated to the target-defining feature, we refer to them as *irrelevant colour singletons*. Second, the target display contained one square and one diamond while the other shapes remained circles. The square and diamond always appeared in opposite hemifields. Half of the participants were instructed to respond to the letter within a square and the other half to the letter within a diamond. As in Experiments 2 and 3, these two shapes and the four letters appeared only in the same original four peripheral boxes used in Experiment 1. Third, because colour was no longer the target-defining feature, all objects in the target display were white. Fourth, because there was no evidence of attentional capture by colour singletons with increased presentation time in Experiments 2 and 3, we therefore used the same cue–target onset interval of 150 ms (50 ms for the cue display and 100 ms for the cue–target interval) as in Experiment 1. We did, however, retain the doubled duration of target display (from 50 ms to 100 ms) because the current shape discrimination is more difficult than the colour discrimination. As a result, the time window for the target-elicited N2pc effect was 350–450 ms after the singleton cue onset, which still corresponds to 200–300 ms after the target onset.

Results

The data analysis was similar to that of Experiment 2. Application of the RT cutoffs eliminated 3.98% of the trials. Rejection of trials with EEG artefacts led to the further elimination of 10.04% of trials, but no more than 25% for any individual participant.

Behavioural data analyses

The behavioural data were analysed as a function of cue validity (valid and invalid). Table 4 shows the mean RT and PE for each of these conditions. The overall cue validity effect was significant on RT (11 ms), $F(1, 23) = 8.09$, $p < .01$, $\eta_p^2 = .26$, and PE (.017), $F(1, 23) = 7.22$, $p < .05$, $\eta_p^2 = .24$. These effects, although small, suggest that some capture can occur even for irrelevant colour singletons. However, even if these effects are real, it would appear that capture is relatively rare. As noted next, the effects were not confirmed by the ERP data reported.

ERP data analyses

Figure 10A and B show the average waveforms for the contralateral and ipsilateral electrode sites, relative to the *singleton* cue location (collapsed

TABLE 4
Mean response times (RT, in ms) and proportion of errors (PE) as a function of cue validity condition (valid and invalid) in Experiment 4

	Cue validity condition		
	Valid	*Invalid*	*Cue validity effect*
RT	755 (25)	766 (25)	11 (4)
PE	.150 (.020)	.167 (.021)	.017 (.005)

The standard error of the mean is shown in parentheses.

across the left and right singleton cue locations), and Figure 10C shows the average difference waveforms (i.e., the N2pc effect). We analysed the difference waveform as a function of singleton-cue/target spatial relationship (same hemifield vs. different hemifields), and singleton cue location (left vs. right) over two different time windows: 200–300 ms after singleton cue onset (to assess the singleton-elicited N2pc effect) and 350–450 ms after singleton cue onset (to assess the target-elicited N2pc effect).

Singleton-elicited N2pc effects. The singleton-elicited N2pc analyses showed no effects to be significant, Fs(1, 23) < 1.0. The overall singleton-elicited N2pc effect (200–300 ms after singleton cue onset) averaged across the two hemifield conditions was only -0.091 μV, $t(23) = -1.18$, $p = .2486$. The singleton-elicited N2pc analyses revealed that the N2pc effect was similar regardless of whether the singleton and target were in the same or different hemifield, $F(1, 23) < 1.0$. Follow-up t-tests revealed that the N2pc effect was nonsignificant both when the irrelevant singleton cue was in the same hemifield as the target (-0.077 μV), $t(23) = -0.85$, $p = .4045$, and when it was in a different hemifield (-0.105 μV), $t(23) = -1.16$, $p = .2587$. Interestingly, there was a clear trend in both conditions for a late N2pc effect (a similar but weaker effect was also apparent in Experiments 1 and 2). However, this cannot easily be construed as evidence for capture by irrelevant colour singletons, for two reasons. First, this trend occurs very late, approximately 100 ms later than capture by relevant colour singletons in Experiments 1 and 2 (see Figure 5 and 8) and numerous previous experiments (e.g., Eimer & Kiss, 2008; Hickey et al., 2006; Kiss, van Velzen, & Eimer, 2008; Lien et al., 2008; Luck & Hillyard, 1994). Second, and more importantly, the effect is in the opposite direction to that predicted by attention capture. The cause of this effect is unclear, but one could speculate that it reflects a volitional (and hence slow) movement of attention away from the irrelevant colour singletons, which participants know to be task-irrelevant. Note that this speculation

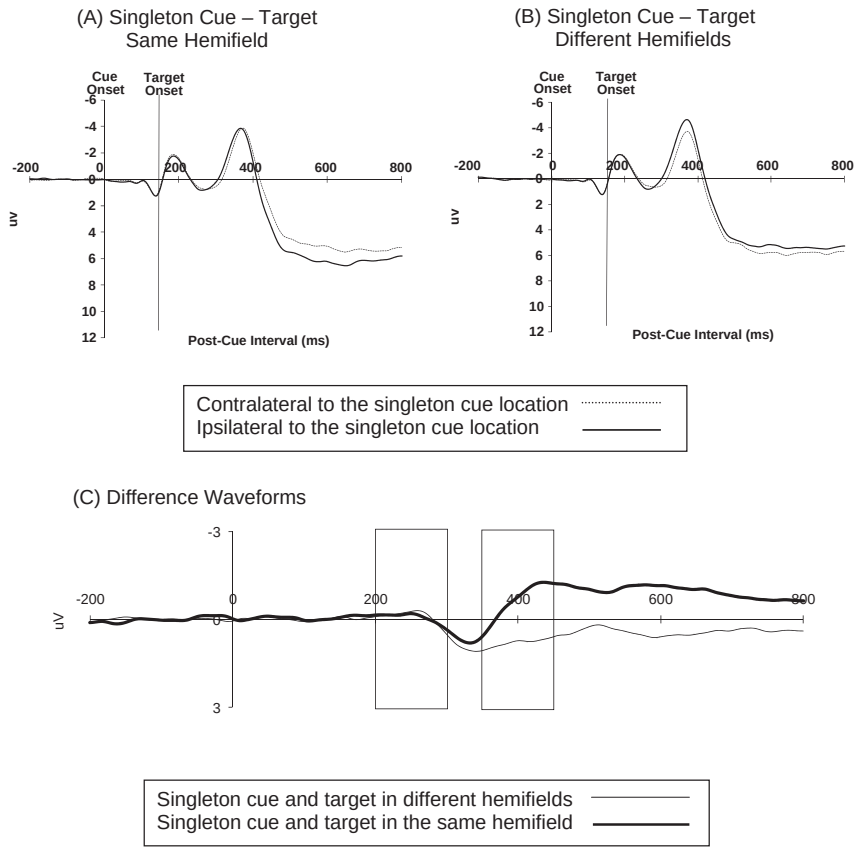

Figure 10. Grand average event-related brain potentials for singleton cues and targets recorded and averaged across the posterior electrode sites contralateral (dashed line) or ipsilateral (solid line) to the singleton cue location in Experiment 4. (A) The average event-related brain potentials when the singleton cue and the target were in the same hemifield. (B) The average event-related brain potentials when the singleton cue and the target were in opposite hemifields. Target onset (represented by a solid vertical line) occurred 150 ms after singleton cue onset. (C) Grand average difference waveforms, calculated by subtracting activity in electrode sites ipsilateral to the singleton cue location from activity in electrode sites contralateral to the singleton cue location as a function of whether the singleton cue and the target were in the same hemifield or different hemifields. The unfilled rectangular boxes indicate the time window used to assess the N2pc effect: 200–300 ms after cue onset (for the singleton-elicited N2pc effect) and 350–450 ms after cue onset (for the target-elicited N2pc effect). Negative is plotted upwards and time zero represents singleton cue onset.

requires only that participants take note of the singleton location. It does not imply actual attentional capture by irrelevant colour singletons, which should have produced an early N2pc effect in the normal direction (not a late N2pc effect in the opposite direction).

Target-elicited N2pc effects. As predicted, the overall target-elicited N2pc effect was negative when the target was in the same hemifield as the singleton cue (−0.648 μV) but was positive when the target was in the opposite hemifield (0.795 μV), $F(1, 23) = 41.56$, $p < .0001$, $\eta_p^2 = .64$. Consistent with findings of the previous experiments, these results confirm that the target captured attention. The overall target-elicited N2pc effect was negative when the singleton cue appeared on the right side (−1.535 μV) and was positive when the singleton cue appeared on the left side (1.682 μV), $F(1, 23) = 8.75$, $p < .01$. The interaction between these two variables was also significant, $F(1, 23) = 5.73$, $p < .05$, reflecting that the N2pc effect was much larger when the target was in the same hemifield as the singleton cue for the right singleton cue than for the left singleton cue (−2.332 μV vs. −0.739 μV, respectively) but was larger when the target was in the opposite hemifield for the left singleton cue than for the right singleton cue (2.329 μV vs. 1.035 μV, respectively).

Discussion

One possible explanation for the lack of capture by irrelevant colour singletons in Experiments 1–3 is that the search for a target colour led to the inhibition of all other colours. Experiment 4 was therefore designed to determine whether colour singletons can capture attention when they are unrelated to the dimension used to find the target. We continued to study capture by colour singletons, which are very salient, but used shape rather than colour to define the target.

Under these conditions, a cue validity effect of 11 ms was obtained; that is, mean RT was faster when the target appeared in the same location as the irrelevant colour singleton rather than another location. The cue validity effect, considered by itself, is consistent with weak or occasional attentional capture by the colour singleton (see Becker, 2007, for a discussion of alternative explanations based on filtering costs). However, there are several reasons to question even weak capture. As it turns out, the N2pc data provide no evidence of capture by the irrelevant colour singleton when the target-defining feature was a shape. The 95% confidence interval for the N2pc effect (averaged across the same and different hemifield conditions) was only -0.091 ± 0.077 μV. By comparison, the relevant colour singleton cues and the targets typically produced N2pc effects of about −0.500 to −1.500 μV in Experiments 1 and 2. Although it is impossible to rule out the possibility of capture on a small percentage of trials, the N2pc data suggest that this percentage is small. Furthermore, to examine whether the small cue validity effect was a true effect, we conducted a behavioural version of this experiment with a relatively large sample size ($N = 70$). The cue validity effect was only 6 ms on RT and was nonsignificant, $F(1, 69) = 1.69$, $p = .1975$, $\eta_p^2 = .02$. Thus, results from this

control experiment and Experiments 1–3 support the conclusion that irrelevant colour singletons do not capture attention.

To summarize, the absence of the N2pc effect in this experiment suggests that colour singletons did not capture attention even though the target was defined by shape and thus there was no need to inhibit specific colours in the target display. We conclude that capture is strongly contingent on top-down attentional control settings, not bottom-up stimulus salience.

GENERAL DISCUSSION

This study examined whether colour singletons can capture attention based purely on salience. Arguably the most compelling evidence for capture by singletons comes from Hickey et al.'s (2006) electrophysiological study. As noted earlier, however, their participants may have been set to look for any singleton. In other words, colour singletons may have captured attention not because of their salience but because participants were looking for them.

Thus, an important aspect of our design was that the target display always consisted of one blue letter, one green letter, one red letter, and one white letter (Experiments 1–3). Because the target itself was never a singleton, singleton-detection mode would not have been successful. With this tighter control over top-down control settings, we asked whether colour singletons still have the power to capture spatial attention involuntarily, using both electrophysiological measures (i.e., N2pc effects) and behavioural measures (i.e., cue validity effects on RT).

Summary of findings

We used a cueing paradigm, in which a colour singleton cue display was followed by a target display. In Experiments 1 and 2, three target colours (red, green, and blue) were used, with each participant responding to only one target colour throughout the experiment. We manipulated the relationship between the colour of the singleton cue and the target-defining colour to form the relevant, irrelevant, and competing singleton conditions. Behavioural data in both experiments showed that only the relevant singleton—drawn in the colour used to find the target—produced a cue validity effect (i.e., faster responses when the target appeared in the same location as the singleton cue). There was no evidence that the irrelevant colour singleton captured attention. The competing singleton condition, meanwhile, pitted an irrelevant colour singleton against background boxes drawn in the relevant target colour. The results suggest that the relevant background items pulled attention away from the more salient colour singleton. In summary, the behavioural data in Experiments 1 and 2 suggest that colour singleton cues do not generally

capture attention. Instead, they appear to capture attention only when they happen to match top-down control settings (what the observer is looking for).

The ERP data in Experiments 1 and 2 provided important converging evidence for this conclusion. The colour singleton cue produced a robust N2pc effect only when it contained the target-defining feature (see Eimer & Kiss, 2008, for similar findings). These data refute an alternative explanation for the small cue validity effect from irrelevant colour singletons, which says that attention was initially captured by the colour singleton, but then returned to a neutral state sometime before target processing required spatial attention. The N2pc data, which provide a continuous measure of attentional allocation over time, offer no hint of such an early shift of spatial attention.

Experiment 3 replicated the absence of the capture effects by irrelevant colour singletons in a design in which participants performed three sessions, each with a different target colour. Experiment 4 investigated whether colour singletons also fail to capture attention when participants search for shapes (rather than colours) in the target display. Under these conditions, there would be less incentive to inhibit specific colours. The results showed that irrelevant colour singletons still produced no detectable N2pc effect, suggesting that they continued to fail to capture attention.

One could argue that an attentional shift need not necessarily produce an N2pc effect, just as it need not produce a cue validity effect. So the absence of such effects does not prove that irrelevant colour singletons did not capture attention. It is conceivable, for example, that irrelevant colour singletons capture attention too briefly to be detected by behavioural or ERP measures. It is also possible that they capture attention, but too rarely to be detected. Nevertheless, it is clear that whereas we found strong, converging evidence for consistent capture by colour singletons when task-relevant, we were unable to find such evidence when they were task-irrelevant.

Pooled analyses of Experiments 1–4

The present results clearly indicate that irrelevant colour singletons did not strongly capture attention. To conduct a sensitive test of whether they might weakly or occasionally capture attention, we conducted a pooled analysis across all of the present experiments. Averaged across all participants, the N2pc effect elicited by the target letter was -0.952 ± 0.061 μV (95% confidence interval).[4] The N2pc effect to relevant colour singletons

[4] We define the N2pc effect with respect to the singleton cue location. As a consequence, when the singleton cue and target are in different hemifields, the polarity of the N2pc effect elicited by the target becomes positive. Thus, before averaging across the same and different hemifield conditions, we first reversed the polarity of the target-elicited N2pc effect for the different hemifield condition.

(Experiments 1 and 2) was nearly as large: -0.708 ± 0.120 μV. However, the N2pc effect to irrelevant colour singletons across all four experiments was negligible: 0.004 ± 0.063 μV, $t(65) = 0.06$, $p = .9525$. Thus, even after allowing for sampling error, the overall N2pc effect produced by irrelevant-singletons was only 0–10% of that produced by an actual target.

The behavioural data, although slightly noisier, suggest a similar conclusion. Relevant colour singletons (Experiments 1 and 2) produced an average cue validity effect of 36 ± 10 ms. However, irrelevant colour singletons (Experiments 1–4) produced an average cue validity effect of 4 ± 5 ms, which was not quite significant, $t(65) = 1.65$, $p = .1032$. The present data cannot rule out the possibility of occasional capture by irrelevant colour singletons (no data set could). However, they do suggest that such capture, if it occurs at all, is relatively rare under the conditions studied.

Although the cue validity effects from irrelevant colour singletons were not significant in the pooled analysis discussed earlier, they were significant in Experiment 4. Furthermore, these effects were significantly larger in Experiment 4 ($M = 11$ ms) than in Experiments 1–3 combined ($M = 0$ ms), $F(1, 64) = 6.87$, $p < .05$, $\eta_p^2 = .10$. If genuine, this effect might be a consequence of making it more difficult to find the target: Mean RT was much longer for targets defined by shape in Experiment 4 (761 ms) than for targets defined by colour in Experiments 1–3 (537 ms). Alternatively, it might reflect a slightly increased susceptibility to capture when the salient stimulus is completely unrelated to the task (as in Experiment 4).

To determine whether this cue validity effect is genuine, we ran an additional 70 participants in a behavioural version of Experiment 4 as described previously. Despite the large sample size, we were unable to confirm the findings of Experiment 4: The cue validity effect was small (6 ms) and nonsignificant. The findings of the Experiment 4 behavioural data were also not confirmed by the EEG data in that same experiment: The N2pc effect for irrelevant singleton cues was small and nonsignificant. At present, the most we can say is that if irrelevant colour singletons have any ability to capture attention at all, there are hints that it is most likely to occur when the target task involves a different dimension. In any case, we can safely conclude that capture effects are small and inconsistent even under these more favourable conditions, making them difficult to detect even with a generous sample size.

The nature of contingent capture

An implication of capture by the relevant singleton cue is that the attentional system failed to distinguish the cue from the target, even though these stimuli were actually quite different. Whereas the target was a letter

occurring during the target frame, the cue was a box occurring earlier in time. One explanation is that people adopt the simplest and most efficient control setting possible. In the present experiments, for instance, this means that participants did not look for a red "L" or a red "T" at a particular point in time. Instead, they simply searched for any red object. This lack of specificity would reduce mental load and allow for more rapid attentional capture. But it comes at the expense of making people vulnerable to capture by another red object, even if it does not resemble the target shape and even if it is presented at the wrong point in time.

One could also argue that the cue validity effect for the relevant singleton cue condition could be explained in terms of an intertrial priming effect (e.g., Found & Müller, 1996; Maljkovic & Nakayama, 1994). That is, when the target and distractor remain the same from one trial to the next, attentional selection might be facilitated by the carryover of target activation and/or distraction inhibition from the preceding trial. Although this explanation sounds plausible, there is evidence against it. Becker (2007) found that an irrelevant singleton did not affect target performance when the colour assignment to the irrelevant distractor and the remaining items switched from the previous trial. Similar findings were obtained with shapes in Lamy and Yashar (2008). Lien, Ruthruff, and Johnston (in press) also examined attention capture under the requirement to frequently change attentional control settings (e.g., from a red target letter to a green target letter). They found that the previous target colour did not capture attention once participants were prompted to look for a different colour. The recently prompted target colour, however, did capture attention, regardless of its status in the previous display.

Can salient stimuli capture attention under other conditions?

A possibility worth considering is that salient stimuli do in fact have the inherent power to capture attention, but this capture can be inhibited by application of a strong top-down set (see Jonides & Yantis, 1988; Remington et al., 1992; Theeuwes & Burger, 1998; Yantis, 1993). In the present study, and in Lien et al. (2008), participants needed to look for a particular colour (Experiments 1–3) or a particular shape (Experiment 4). It is possible that this top-down attentional control setting was strong enough to override attentional capture by the singleton, even a singleton on a dimension that is not task-relevant (see also Folk, Remington, & Johnston, 1993). There are many cases in the real world in which one is not looking for anything in particular and thus one has no need to establish a strong top-down control setting. Under such conditions, salient stimuli might routinely capture attention. As an example, the sudden onset of a warning light in a cockpit

might capture the pilot's visual attention when he/she is not actively looking for any other object (as would likely be the case during the majority of a flight).

A related possibility is that, in the absence of specific goal, people tend to be looking for salient stimuli or new stimuli, because such stimuli are especially likely to represent dangers or opportunities. On this view, capture by salient stimuli is, in a sense, still contingent on top-down settings. Note that such a set for salient stimuli might be abandoned as soon as one has an imperative need to search for a specific feature.

Another caveat regarding the present conclusions is that some recent studies have argued that the ability of salient, irrelevant distractors to capture attention may strongly depend on the attentional window (e.g., Belopolsky et al., 2007; Proulx & Egeth, 2006; Theeuwes, 2004). For instance, Belopolsky et al. (2007) had participants search for the letter "E" or "H" among either two or eight other letters. In the target display, one of the letters was red while the others were green. The red letter was no more likely to be the target ("E"/"H") than was any other letter. The authors manipulated the size of the attentional window by asking participants to search only when the global shape of the letters formed an upwards-pointing triangle rather than a downwards-pointing triangle (the diffuse attention condition) or to search only when the central object was a circle rather than a square (the focused attention condition). In the diffuse attention condition, the search slope was much shallower when the target was the singleton object, suggesting that it captured attention and therefore was one of the first items searched. This effect was not evident in the focused attention condition. They concluded that attentional capture by irrelevant, salient objects occurs only when the task encourages a more distributed allocation of attention.

Belopolsky et al.'s (2007) findings, if taken at face value, might seem to provide a ray of hope for explaining the failure of colour singletons to capture attention in our study. However, it seems clear that simple colour searches such as ours produce flat search slopes (see e.g., Duncan, 1989, Exp. 1; Kaptein, Theeuwes, & van der Heijden, 1995), consistent with parallel search and a diffuse allocation of attention. In fact, we have verified that, using the stimuli and tasks like the present study, search slopes are nearly flat (Lien et al., in press). Thus, the mode of attention in the present study is the kind that, according to Belopolsky et al., is most likely to produce attentional capture. Furthermore, if our target displays somehow encouraged an attentional mode that prevents attention capture, then one might also expect no capture by *relevant* colour singleton cues. Contrary to this prediction, we found clear evidence that relevant colour singleton cues captured attention in both Experiments 1 and 2.

CONCLUSIONS

It has recently been argued, using electrophysiological evidence, that attentional allocation is driven by the bottom-up salience of a singleton, independent of the target-defining feature (Hickey et al., 2006). After eliminating any incentive to look for singletons, however, we found that colour singletons rarely (if ever) had the power to capture attention (see also Eimer & Kiss, 2008). The colour singleton elicited involuntary attentional capture only when it happened to also share the property that was critical for finding the target. In other words, our data indicate that capture is contingent not on stimulus salience but rather on a strong match with top-down control settings.

REFERENCES

Ansorge, U., & Heumann, M. (2003). Top-down contingencies in peripheral cuing: The roles of color and location. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 937–948.

Ansorge, U., & Horstmann, G. (2007). Preemptive control of attentional capture by color: Evidence from trial-by-trial analysis and ordering of onsets of capture effects in RT distributions. *Quarterly Journal of Experimental Psychology*, *60*, 952–975.

Ansorge, U., Horstmann, G., & Carbone, E. (2005). Top-down contingent capture by color: Evidence from RT distribution analyses in a manual choice reaction task. *Acta Psychologica*, *120*, 243–266.

Arnott, S. R., Pratt, J., Shore, D. I., & Alain, C. (2001). Attentional set modulated visual areas: An event-related potential study of attentional capture. *Cognitive Brain Research*, *12*, 383–395.

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.

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

Becker, S. I. (2007). Irrelevant singletons in pop-out search: Attentional capture or filtering costs? *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 764–787.

Belopolsky, A. V., Zwaan, L., Theeuwes, J., & Kramer, A. F. (2007). The size of an attentional window modulates attentional capture by color singletons. *Psychonomic Bulletin and Review*, *14*, 934–938.

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.

Duncan, J. (1989). Boundary conditions on parallel processing in human vision. *Perception*, *18*, 457–469.

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

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

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

Folk, C. L., & Remington, R. W. (2006). Top-down modulation of preattentive processing: Testing the recovery account of contingent capture. *Visual Cognition*, *14*, 445–465.

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.

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a "dimension-weighting" account. *Perception and Psychophysics*, *58*, 88–101.

Gibson, B., & Jiang, Y. (1998). Surprise! An unexpected color singleton does not capture attention in visual search. *Psychological Science*, *9*, 176–182.

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

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

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

Kaptein, N. A., Theeuwes, J., & van der Heijden, A. H. C. (1995). Search for a conjunctively defined target can be selectively limited to a color-defined subset of elements. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 1053–1069.

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 and Psychophysics*, *61*, 1009–1023.

Kiss, M., Jolicoeur, P., Dell'Acqua, R., & Eimer, M. (2008). Attentional capture by visual singletons is mediated by top-down task set: New evidence from the N2pc component. *Psychophysiology*, *45*, 240–249.

Kiss, M., van Velzen, J., Eimer, M. (2008). The N2pc component and its links to attention shifts and spatially selective visual processing. *Psychophysiology*, *45*, 240–249.

Lachter, J., Forster, K. I., & Ruthruff, E. (2004). Forty years after Broadbent: Still no identification without attention. *Psychological Review*, *111*, 880–913.

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 and Review*, *10*, 621–629.

Lamy, D., & Yashar, A. (2008). Intertrial target-feature changes do not lead to more distraction by singletons: Target uncertainty does. *Visual Research*, *48*, 1274–1279.

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

Lien, M.-C., Ruthruff, E., & Johnston, J. C. (in press). Attentional capture with rapidly changing attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*.

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

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

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

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory and Cognition*, *22*, 657–672.

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.

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* (pp. 77–92). Amsterdam: Elsevier Science.

Proulx, M. J., & Egeth, H. E. (2006). Target-nontarget similarity modulates stimulus-driven control in visual search. *Psychological Bulletin and Review*, *13*, 524–529.

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

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

Ruz, M., & Lupiánez, J. (2002). Attentional capture and exogenous orienting: Upon their automaticity and sensitivity to endogenous control. *Psicológica*, *23*, 283–309.

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

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

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

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

Theeuwes, J., Atchley, P., & Kramer, A. F. (2000). On the time course of top-down and bottom-up control of visual attention. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (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.

Vogel, E. K., Luck, S. J., & Shapiro, K. L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1656–1674.

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. (2000). Goal-directed and stimulus-driven determinants of attentional control. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 73–103). Cambridge, MA: MIT Press.

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 & Performance*, *16*, 121–134.

Manuscript received December 2008
Manuscript accepted April 2009
First published online July 2009