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The absence of a visual stimulus can trigger task-set-independent attentional capture

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Abstract

We investigated whether the absence of one item in a regularly spaced visual array (gap cue) captures attention in a task-set-independent fashion. Participants searched for a large target among medium-size distractors (size task) or a red target among gray distractors (color task). Target arrays were preceded by uninformative cue arrays that contained a color singleton or a gap cue. The N2pc component was measured as an index of attentional capture. Color singleton cues captured attention only in the color task, but gap cues captured attention in both tasks. For cue arrays containing a color singleton and a gap cue on opposite sides, an N2pc was triggered by the color singleton in the color task. The absence of an item in a regular array triggered task-set-independent attentional capture when it was the only unique display feature, but not when a competing set-matching singleton was simultaneously present.

Descriptors: Spatial attention, Top-down control, Event-related potentials, N2pc

The attentional selection of visual objects can occur in a stimulus-driven (bottom-up) fashion or can be guided by top-down information about currently task-relevant stimulus features. Even though it is widely assumed that selective attention is controlled by the interplay of top-down and bottom-up factors (e.g., Desimone & Duncan, 1995; Wolfe, 2007), their relative importance during visual search for salient visual events such as feature singletons is still a matter of intense debate. On the one hand, it has been argued that the initial allocation of attention to visual events is driven exclusively by bottom-up salience and is unaffected by top-down search goals (e.g., Theeuwes, 2010). Evidence for bottom-up attentional capture comes from the observation that the presence of a salient color singleton distractor in visual search arrays delays response times (RTs) to simultaneously present target shape singletons, in spite of the fact that color is known to be a task-irrelevant attribute (Theeuwes, 1991). On the other hand, there is also strong evidence from spatial cueing studies that attentional capture by feature singletons is contingent on top-down task settings (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992). When spatially nonpredictive singleton cues precede visual search displays, the presence or absence of attentional capture by these cues can be inferred from the pattern of spatial cueing effects. Faster RTs to visual search targets at cued relative to uncued locations indicative of attentional capture were observed when cue features matched the current task set (e.g., for color singleton cues in blocks where targets were also color singletons), but not when cue features were task irrelevant (e.g., for color singleton cues in blocks with onset targets). This finding has led to the contingent involuntary orienting hypothesis (Folk et al., 1992), which postulates that attentional capture is triggered by salient visual stimuli only when they possess currently task-relevant attributes.

Support for task-set-contingent attentional capture has recently been provided by event-related brain potential (ERP) studies, which have employed the N2pc component as an online electrophysiological marker of capture. The N2pc is an enhanced negativity over posterior scalp electrodes contralateral to the side of attended stimuli that is triggered around 200 ms after the onset of visual search arrays and is known to reflect the attentional selection of candidate target items among distractors in visual search (e.g., Eimer, 1996; Luck & Hillyard, 1994). As predicted by the contingent involuntary orienting hypothesis, the N2pc is triggered by visually salient singleton cues only when these cues match target-defining features, whereas no N2pc is elicited in response to physically identical cues when task instructions are changed so that their properties no longer correspond to a currently active task set (e.g., Eimer & Kiss, 2008; Eimer, Kiss, Press, & Sauter, 2009; Lien, Ruthruff, Goodin, & Remington, 2008).

Task-set contingent attentional capture effects have been demonstrated for a number of different stimulus features, including color, shape, apparent motion, and abrupt onset. In a recent ERP study (Kiss & Eimer, 2010), we investigated whether attentional capture by size singletons is also contingent on current task settings. In different blocks, participants searched for either a large or a small target bar that was presented in circular search arrays among medium-size distractors. These search arrays were preceded by circular cue arrays that contained a

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spatially uninformative size singleton (one item that was smaller or larger than all other elements of the cue array). Results demonstrated that the ability of size singletons cues to capture attention was determined by participants' search intentions. Behavioral spatial cueing effects and N2pc components indicative of attentional capture were triggered by size singleton cues only when their relative size matched the size of the current search target (e.g., small cues during search for small targets), but not when there was a mismatch (e.g., small cues during search for large targets). These results show that attentional capture by size singletons is controlled by top-down task sets in which the task-relevant size is defined in a direction-specific fashion relative to the stimulus context (i.e., larger/smaller than the background items).

Although these observations are fully in line with previous behavioral and ERP studies demonstrating task-set-contingent involuntary attentional capture (e.g., Eimer & Kiss, 2008; Folk et al., 1992), other results from the same experiment (Kiss & Eimer, 2010) suggest that singleton capture may not always be under full top-down control. In addition to small and large singleton cues, a third circular cue array type was employed, which contained equally spaced identical gray items, except for one location on the left or right side that remained empty. These gap cue arrays (referred to as "nothing" cues in this previous study) were included to test whether the absence of a stimulus in a circular array might be attentionally equivalent to a (very small) size singleton cue and might therefore capture attention in a task-set-contingent fashion. However, results did not confirm this prediction. Gap cues elicited behavioral spatial cueing effects and N2pc components indicative of attentional capture regardless of whether participants searched for small or large targets. This observation indicates that the absence of a single item in a regularly spaced circular stimulus array might attract attention in an involuntary, task-set-independent fashion, perhaps because of the strong bottom-up salience of the luminance discontinuity in such gap cue arrays. This would be an important conclusion, because the agreed list of features that can capture attention in a purely bottom-up fashion is very short indeed and so far only includes abrupt luminance onsets and/or the appearance of new perceptual objects (e.g., Yantis & Hillstrom, 1994; Yantis & Jonides, 1984).

One aim of the present study was to provide a fuller investigation of the hypothesis that the absence of an item in a structured visual array will capture attention independently of which feature-specific top-down task set is currently active. A second aim was to substantiate the surprising if not counterintuitive observation from our previous experiment (Kiss & Eimer, 2010) that an N2pc component can be triggered by the *absence* of a visual stimulus. We used the spatial cueing paradigm introduced by Folk et al. (1992) where spatially uninformative singleton cues precede visual search arrays, and participants are instructed to detect singleton targets that are defined by a specific feature. In two different parts of the present experiment, search arrays contained a size singleton target (a large bar among medium-size bars) or a color singleton target (a red bar among gray bars). Search arrays were preceded with equal probability and in random order by one of three circular cue arrays. Gap cue arrays were identical to the arrays used in our previous study (Kiss & Eimer, 2010). They contained five equally spaced gray items along the circumference of a virtual circle and one lateral position that remained unfilled (Figure 1). Red singleton cue arrays contained one red item on the left or right side together with five gray items, analogous to the cues used in previous ERP studies of color-contingent attentional capture (Eimer & Kiss, 2008; Eimer et al., 2009). Combined cue arrays contained a red singleton item on one side and an unfilled array position in the opposite hemifield.

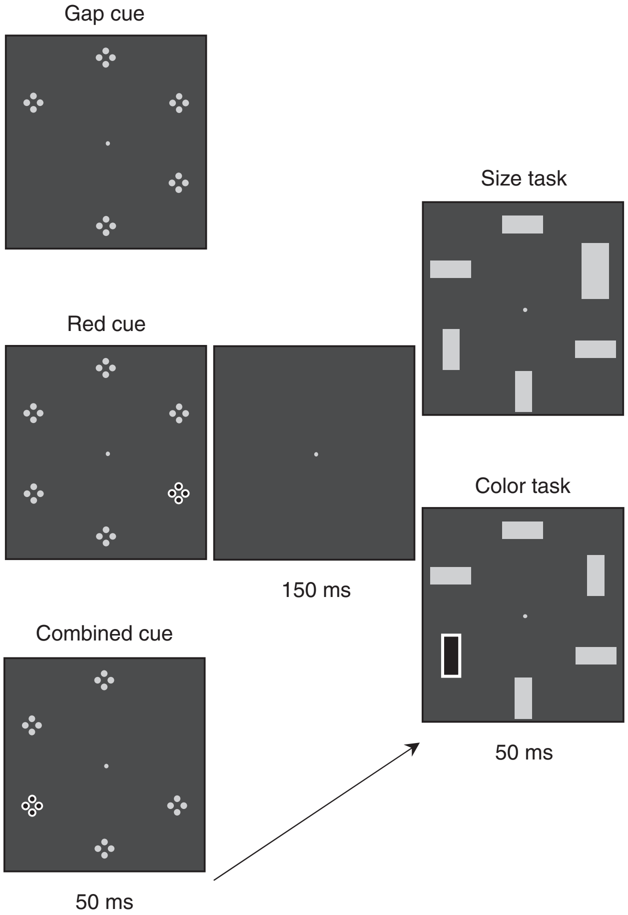

Figure 1. Cue and target displays used. In separate blocks, participants searched for a large bar among medium-size bars (size task) or for red (shown here in black with white outline) among gray bars (color task) and reported target orientation (horizontal or vertical) with a key press. Search arrays were preceded by three different types of spatially nonpredictive cue displays. In gap cue arrays, all cue items were gray, and one lateral cue item position was left unfilled. In red singleton cue arrays, one item on the left or right side was red and was presented among five gray items. Combined cue arrays contained a lateral red color singleton item and one unfilled position on the diagonally opposite side.

Behavioral spatial cueing effects and N2pc components triggered in response to these three different cue arrays were measured during visual search for a size-defined or a color-defined target in order to assess and contrast the ability of color singleton cues and gap cues to capture attention under conditions where either size or color is the target-defining feature. Previous behavioral and ERP studies on the task-set-contingent nature of attentional capture by color singletons (e.g., Eimer & Kiss, 2008; Folk et al., 1992) yield straightforward predictions for trials with red singleton cue arrays: Red singleton cues should capture attention when participants search for red singleton targets, and this should be reflected by a behavioral spatial cueing effect and an N2pc component triggered by these cues. In contrast, no behavioral and ERP correlates of attentional capture should be observed for the same red singleton cues in blocks where size is the task-relevant feature. The critical question concerned the attentional capture effects observed for cue arrays that contained an unfilled position on the left or right side. Because the location of a large target among medium-size distractors in the size task was characterized by a luminance discontinuity in the search array, we assumed that the luminance discontinuity associated with the absence of an item at a regular position in a structured cue array can be regarded as a feature singleton in the size dimension. If such gap cues attract attention in a task-set-independent fashion, they should trigger attentional capture not only when size is relevant, but also during search for color singletons where targets are defined in an entirely different dimension. In this case, behavioral spatial cueing effects and N2pc components should be found for gap cues both when participants search for large targets and when they search for red targets. In contrast, the absence of behavioral and ERP evidence for attentional capture by gap cue arrays during search for color targets would demonstrate the inability of these cues to attract attention when targets are defined in a dimension other than size, which would provide evidence for the task-set-contingent nature of attentional capture by gap cues.

Combined cue arrays that contained a red singleton cue on one side and a gap cue at the diagonally opposite location on the other side were included in this study to investigate attentional competition between simultaneous gap cues and red singleton cues and how this competition is resolved during search for size or color singletons. In blocks where participants searched for large targets, red singleton cues should not trigger attentional capture (see above) and should therefore not compete with gap singletons in the opposite hemifield. Therefore, attentional capture by gap singleton cues in combined cue arrays, as reflected by behavioral spatial cueing effects and an N2pc component in response to these cues, should be the same as attentional capture by gap cues without additional color singleton. The critical question was what type of attentional capture effects would be observed for combined cues in blocks where color was task relevant. If gap singletons attract attention in a stimulus-driven and task-set-independent fashion, they should produce behavioral spatial cueing effects and elicit an N2pc component even when targets are color defined and a task-set-matching color singleton is simultaneously present on the opposite side. Alternatively, attentional competition between a gap and a red singleton in combined cue arrays might be decided in a top-down fashion in favor of the task-set-matching color singleton. In this case, spatial cueing effects and an N2pc component should be found for color singleton cue locations, but not for the location occupied by gap singleton cues.

Method

Participants

Thirteen volunteers took part in this experiment. One had to be excluded because of technical problems during electroencephalogram (EEG) recording. The remaining 12 participants (3 men; mean age 26.3 years) were all right-handed and had normal or corrected-to-normal vision.

Stimuli and Procedure

Stimuli were presented on a CRT monitor (100-Hz refresh rate) against a black background. In each trial, a circular search display was preceded by a circular task-irrelevant cue display (Figure 1). The search array consisted of six bars that were randomly oriented either horizontally or vertically and located at equidistant positions along the circumference of an imaginary circle, at a distance of 4.1° from the central fixation point. In large target blocks, all bars were gray (CIE *x*/*y* values .286/.312), and the target bar was larger (0.6° × 1.2°) than the five distractor bars (0.4° × 0.8°). In blocks with red targets, all bars in the search array were identical in size (0.4° × 0.8°), and participants had to detect a red target bar (CIE *x*/*y* values .619/.339) among gray bars. Red and gray stimuli were equiluminant (10.3 cd/m^2). Targets appeared with equal probability and in random order at one of the four positions on the left or right side, but never at the top or bottom position.

Search arrays were preceded by one of three different types of cue arrays. Cue array items occupied the same positions as the items in subsequent target arrays. Each item in the cue display had a size of 0.4° × 0.4° and was composed of four closely aligned dots. Unilateral gap cue arrays contained five gray items, with one regular position on the left or right side of the cue display (but never at the top or bottom position) left unfilled. Red cue arrays contained one red item at one of the four lateral locations among five gray items. Combined cue arrays contained one red singleton item on one side of the display and one unfilled position at the diagonally opposite location, together with four gray items (see Figure 1). In all blocks, these three cue array types were presented in random order and with equal probability across trials, that is, each cue type appeared in one third of all trials. The location of singleton items in the cue arrays was spatially uninformative with respect to the location of the subsequent search target (25% validity).

The cue display was presented for 50 ms, followed by a blank fixation-point display (150-ms duration) and the search display that appeared for 50 ms. The interval between search array offset and the onset of the cue array on the next trial was 1450 ms. Participants' task was to detect the large or the red target bar (in separate blocks) and report its orientation (vertical or horizontal) by pressing one of two response buttons with their left or right index finger. They were instructed to respond as fast and accurately as possible to search arrays while maintaining central fixation. Large bars or red bars served as targets in eight successive experimental blocks, with task order counterbalanced across participants. Each block contained 96 trials, resulting in a total of 1,536 trials.

EEG Recording and Analysis

EEG was DC recorded from 23 scalp electrodes mounted in an elastic cap at standard positions of the extended 10/20 system at sites Fpz, Fz, F3, F4, F7, F8, FC5, FC6, Cz, C3, C4, T7, T8, CP5, CP6, Pz, P3, P4, P7, P8, PO7, PO8, and Oz. The continuous EEG was sampled at a rate of 500 Hz and digitally low-pass filtered with a 40-Hz Butterworth filter. No further filters were applied after EEG acquisition. All electrodes were online referenced to the left earlobe and re-referenced off-line to averaged earlobes. The continuous EEG was epoched into intervals starting 100 ms before cue onset until 500 ms after cue onset. Trials containing saccades, blinks, or muscle artifacts (HEOG channel exceeding ± 30 μV; VEOG channel ± 60 μV; all other channels ± 80 μV) and trials with incorrect responses were removed from the analysis.

Average waveforms in response to cue arrays were computed for all combinations of task (large target vs. red target), cue type (gap cue, red cue, combined cue), and cue side (left vs. right). For combined cues, cue side was defined relative to the position of the cue item that matched the current target-defining dimension (gap cue in blocks with large targets; red cue in blocks with red targets). The N2pc in response to the cue was quantified at lateral posterior electrode sites PO7 and PO8 on the basis of ERP mean amplitudes computed in the 200–280-ms interval after cue onset. N2pc mean amplitudes were entered into a repeated-measures analysis of variance (ANOVA) with factors task, cue type, cue side, and contralaterality (electrode contralateral vs. ipsilateral to the visual field of the singleton item in the cue array; defined for combined cues relative to the task-matching feature). Greenhouse–Geisser corrections were applied where appropriate.

Results

Behavioral Data

Figure 2 shows mean correct RTs obtained in blocks where participants searched for large targets (size task) or red targets (color task), separately for trials in which search arrays were preceded by gap cues, red cues, or combined bilateral cues. RTs are displayed separately for trials where targets appeared at the same location as a gap cue, at the same location as the red cue, or at one of the remaining uncued positions. Spatial cueing effects indicative of attentional capture were observed for gap cues in blocks where participants searched for large targets. Interestingly, gap cues also produced spatial cueing effects in blocks in which red color singletons served as targets. In contrast, red cues only triggered spatial cueing effects in blocks with red targets, but not when participants searched for large target bars. For combined cue arrays, the direction of attentional capture effects was also determined by top-down task set. In blocks with large targets, RTs were faster for targets at the location of a gap cue relative to trials where targets appeared at the location of a red cue or at an uncued location. When participants searched for red targets, RTs were faster when these targets appeared at the location of a red cue, relative to targets at the location of a gap cue or at an uncued location.

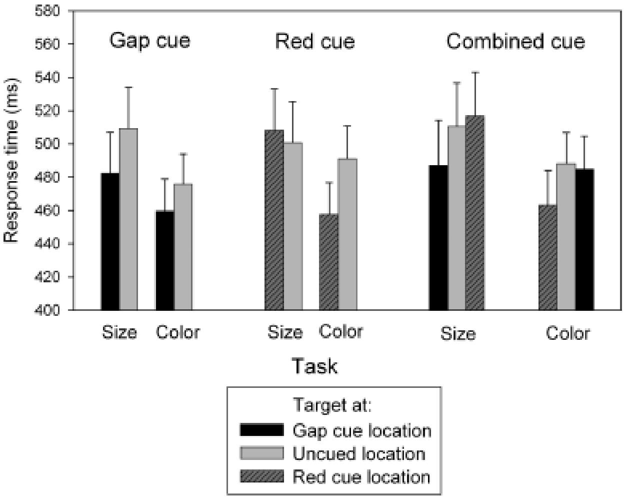

Figure 2. Mean correct response times obtained in the size task and color task, shown separately for target arrays preceded by gap cues, red cues, or combined cue arrays, as a function of the target position relative to the cue. For combined cue arrays, RTs are shown separately for trials where targets appeared at the same location as the red singleton cue, the gap cue, or at one of the two remaining uncued locations. Error bars represent standard errors of the mean.

RTs were analyzed separately for trials with unilateral cues and with combined cues. The analysis of unilateral cue trials included the factors cue type (gap cue vs. red cue), task (large target vs. red target), and target position (cued vs. uncued). There were main effects of target position, $F(1,11) = 85.5$, $p < .001$, and cue type, $F(1,11) = 10.9$, $p < .01$, reflecting overall faster RTs on cued-location trials as compared to uncued-location trials, and faster RTs on trials with gap cues as compared to trials with red cues. The effect of task was marginally significant, $F(1,11) = 4.8$, $p = .051$, due to faster RTs for red targets relative to large targets. Most importantly, there was a three-way interaction between cue type, task, and target position, $F(1,11) = 44.3$, $p < .001$, demonstrating that attentional capture effects triggered by unilateral gap cues and red cues were modulated by the current task set. Separate follow-up analyses were conducted for trials with gap cues and red cues. For gap cues, main effects of task, $F(1,11) = 5.2$, $p < .05$, and target position, $F(1,11) = 85.0$, $p < .001$, were accompanied by a Task × Target Position interaction, $F(1,11) = 8.2$, $p < .02$, as spatial cueing effects elicited by gap cues were larger when participants searched for large targets than when they searched for red targets (27 ms vs. 16 ms; see Figure 2). However, spatial cueing effects were significant in both tasks, both $t(11) > 5.4$, both $p < .001$. For red cues, a main effect of target position, $F(1,11) = 15.9$, $p < .01$, was accompanied by a Task × Target Position interaction, $F(1,11) = 29.6$, $p < .001$. This was because a spatial cueing effect indicative of attentional capture (33 ms) was present in blocks with red targets, $t(11) = 5.2$, $p < .001$, whereas a small but reliable inverted spatial cueing effect (with RTs to targets at uncued locations 7 ms faster than RTs to targets at cued locations) was obtained in blocks with large targets, $t(11) = 2.5$, $p < .05$.

In the analysis of RTs on trials with combined cues, the factor cue type was omitted, and the factor target position now had three levels (same as gap cue, same as red cue, uncued). No significant main effects of task or target position were observed, both $F(1,11) < 3.0$, both $p > .115$. Importantly, a significant Task × Target Position interaction was present, $F(2,22) = 17.3$, $p < .001$, demonstrating that when a gap cue and a red cue were presented simultaneously in opposite hemifields, their respective ability to capture attention was determined by top-down task set. In blocks where participants searched for large targets, RTs were 23 ms faster when these targets appeared at the same position as the gap cue relative to when they appeared at an uncued location, $t(11) = 4.1$, $p < .01$. RTs for large targets at the location of a red cue did not differ from RTs to large targets at the remaining two uncued locations, $t < 1.1$. In blocks where red singletons served as targets, a spatial cueing effect (25 ms) indicative of attentional capture was found for red targets at the location of a red cue relative to targets at uncued locations, $t(11) = 4.0$, $p < .01$. In contrast, and importantly (see Discussion), RTs to red targets at the position of a preceding gap cue did not differ from RTs to red targets at one of the two uncued locations, $t < 1.1$.

Two additional analyses were conducted to investigate whether the presence of an additional singleton in the opposite hemifield reduced the RT cueing effect elicited by task-matching cues relative to trials where this additional task-irrelevant singleton was absent. The magnitude of behavioral attentional capture effects triggered by gap cues during search for large targets was not modulated by the simultaneous presence of a red singleton in the opposite hemifield. Overall spatial cueing effects (i.e., RT differences between trials with large targets at the location of a preceding gap cue and trials with large targets at other locations) did not differ significantly between trials with unilateral gap cues and combined cues, $F < 1$. In blocks with red targets, spatial cueing effects induced by red cues (i.e., RT differences between trials with red targets preceded by red cues at the same location and trials with red targets at other locations) were numerically larger in trials without a contralateral gap cue than in trials where a gap cue was present (33 ms vs. 24 ms), and this difference approached significance, $F(1,11) = 4.5$, $p = .057$.

In trials with unilateral cues, error rates did not differ between the two tasks (3.0% for blocks with large targets and 2.9% for blocks with red targets; $F < 1$). In trials with combined cues, a main effect of task, $F(1,11) = 9.7$, $p < .01$, reflected more errors in the large target condition than in the red target condition (4.3% vs. 2.3%, respectively). Together with the marginally significant RT delay in the size task, this indicates that this task was slightly more difficult than the color task. There were no main effects or interactions involving cue type or target position for error rates.

ERP Data

Figure 3 shows grand-averaged ERP waveforms elicited in the 300-ms interval following cue array onset at posterior electrode sites PO7 and PO8 contralateral and ipsilateral to a singleton item in the cue array. ERPs are shown separately for both tasks (search for large target and search for red targets) and for the three different cue arrays (unilateral gap cues, unilateral red cues, bilateral combined cues). For ERPs in response to combined cue arrays, contralateral and ipsilateral waveforms are defined relative to the position of the task-matching cue (gap cues in blocks with large targets, red cues in blocks with red targets). Unilateral gap cues triggered an N2pc not only when large bars served as targets, but also in blocks where participants searched for red targets (Figure 3, top panel). In contrast, unilateral red cues elicited an N2pc only when red bars were task relevant, and no N2pc was apparent for these cues in blocks where targets were large bars (Figure 3, middle panel). For combined cue arrays, where a gap cue and a red cue were simultaneously present in opposite hemifields, the polarity of the N2pc was determined by top-down task set. An N2pc was triggered contralateral to gap cues in blocks with large targets, and contralateral to red cues in blocks with red targets (Figure 3, bottom panel).

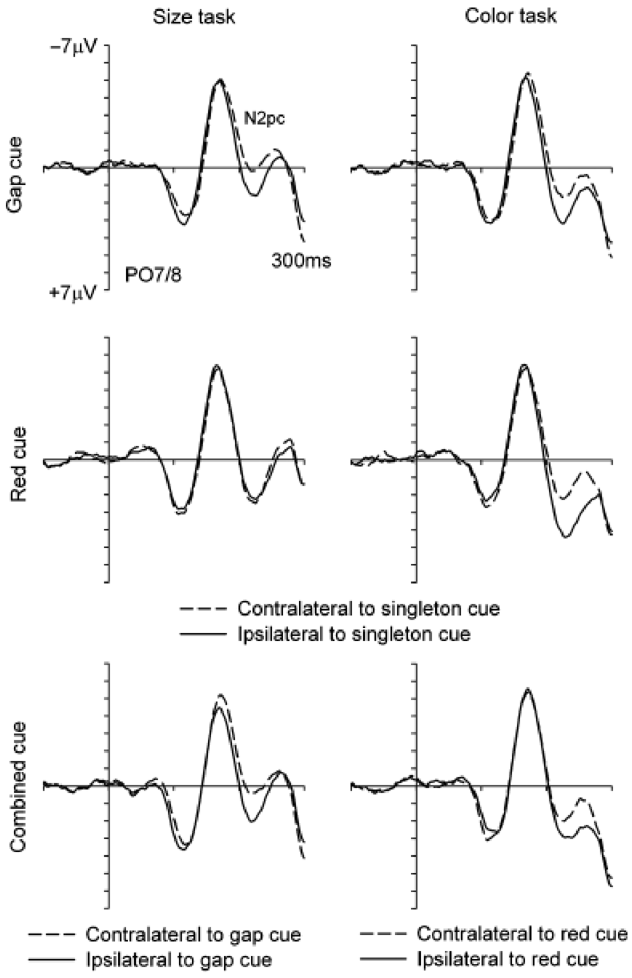

Figure 3. Grand-average ERPs obtained in the 300-ms interval after cue array onset at lateral posterior electrodes PO7 and PO8 contralateral (dashed lines) and ipsilateral (solid lines) to the location of a feature singleton item in the cue array. Waveforms are shown separately for gap cues, red cues, and combined cues for the size task and color task, respectively. For combined cue arrays, contralateral and ipsilateral ERPs are defined relative to the location of the task-matching singleton item (gap cues in blocks with large targets; red cues in blocks with red targets).

Statistical analyses confirmed these observations. An omnibus ANOVA of ERP mean amplitudes in the 200–280-ms interval after cue onset was conducted with the factors cue type (unilateral gap cue, unilateral red cue, bilateral cue), task (large target vs. red target), cue side (left vs. right hemifield), and contralaterality (for bilateral cues defined with respect to the side of the task-matching cue; see above). A main effect of contralaterality, $F(1,11) = 19.9$, $p < .001$, reflecting the presence of an N2pc in response to the cue arrays, was accompanied by a Cue Type × Task × Contralaterality interaction, $F(2,22) = 11.8$, $p < .001$. To explore this interaction, separate ANOVAs were conducted for each of the three cue types. For unilateral gap cues, a main effect of contralaterality was present, $F(1,11) = 14.8$, $p < .01$. There was no interaction between task and contralaterality, $F < 1$, demonstrating that an N2pc of similar size was elicited by gap cues regardless of whether participants searched for large targets or for red targets. Follow-up analyses confirmed the presence of a reliable N2pc to gap cues in both tasks, both $F(1,11) > 10.5$, both $p < .01$. For unilateral red cues, a main effect of contralaterality, $F(1,11) = 9.2$, $p < .05$, was accompanied by a Task × Contralaterality interaction, $F(1,11) = 10.6$, $p < .01$. Follow-up tests confirmed the presence of an N2pc to red cues when participants searched for red targets, $F(1,11) = 10.4$, $p < .01$. In contrast, red cues did not trigger a reliable N2pc during search for large targets ($F < 1$). In the analysis of ERPs in response to combined cues, with contralaterality defined relative to the location of the task-matching cue, a main effect of contralaterality, $F(1,11) = 27.6$, $p < .001$, was present, but there was no interaction between task and contralaterality, $F < 1$. Follow-up analyses confirmed the presence of a reliable N2pc contralateral to the side of the gap cue in blocks where participants searched for large targets, $F(1,11) = 15.9$, $p < .01$, and contralateral to the side of the red cue in blocks where red bars were task relevant, $F(1,11) = 6.7$, $p < .05$ (see Figure 3).

Two additional analyses investigated whether the presence of an additional singleton cue in the opposite hemifield resulted in a reduction of the N2pc to task-matching cues relative to trials where this additional task-irrelevant singleton was absent. The N2pc to gap cues in blocks where large bars served as targets was unaffected by the presence of a red cue in the opposite hemifield, as demonstrated by the absence of an interaction between cue type (unilateral vs. bilateral) and contralaterality, $F < 1$. In contrast, the analogous analysis conducted for red cues in blocks with red targets revealed a Cue Type × Contralaterality interaction, $F(1,11) = 10.3$, $p < .01$, indicating that the presence of a gap cue in the opposite hemifield reduced N2pc amplitude in response to red cues (see Figure 3).

Discussion

We investigated whether the absence of a single item in an otherwise regularly spaced array of visual stimuli would capture attention regardless of which dimension is currently task relevant, or whether attentional capture by such gap cues is contingent on current top-down task sets. Behavioral spatial cueing effects and N2pc components indicative of attentional capture were measured in response to gap cues and to red singleton cues that preceded search arrays containing either a large target among medium-size distractors (size task) or a red target among gray distractors (color task).

As predicted, attentional capture by color singleton cues was fully contingent on the current top-down task set. Behavioral spatial cueing effects and N2pc components were elicited by these cues only in the color task, but not in the size task, thereby confirming results from previous behavioral and ERP studies of task-set-contingent attentional capture by color singletons (e.g., Eimer & Kiss, 2008; Folk et al., 1992). A different pattern of results was obtained for gap cue arrays. As expected, these cues triggered behavioral spatial cueing effects and N2pc components during search for large targets. In line with previous observations (Kiss & Eimer, 2010), this demonstrates that gap cues capture attention under conditions where size is the task-relevant dimension. Importantly, similar behavioral and ERP effects were observed for gap cues when participants searched for red singleton targets, suggesting that these cues trigger attentional capture even when a dimension other than size (e.g., color) is task relevant. This difference in the pattern of attentional capture effects for gap and red singleton cue arrays (task-set-contingent capture for red singleton cues, task-set-independent capture for gap cues) suggests qualitative differences in the degree of attentional top-down control between these two types of singletons and is consistent with the hypothesis that attentional capture by gap cues is unaffected by currently active task sets.

The apparent task-set-independent nature of attentional capture by gap cue arrays may be due to the salience of these cues. A luminance discontinuity associated with the absence of an item in an otherwise regular stimulus array represents a highly salient signal (albeit one that requires the analysis of contextual information across the visual field, and cannot be based on local mechanisms in low-level areas such as V1; see Li, 2002). Such a signal may override current top-down attentional control settings and thus trigger attentional capture in a purely stimulus-driven fashion (see Theeuwes, 2010, for a salience-based bottom-up account of attentional capture). Along similar lines, the observation that attentional capture by color singleton cues was task-set dependent may be due to the relatively lower bottom-up salience of these singletons, which may have enabled top-down control to prevent attentional capture when color was task irrelevant. If bottom-up capture is a function of relative stimulus salience and if gap cues are more salient than red singleton cues, one would expect to find task-set-independent salience-driven attentional capture by gap cues also in combined cue arrays where they are accompanied by a color singleton in the opposite hemifield. Furthermore, this should be the case regardless of whether size or color is currently task-relevant.

In fact, the results obtained in response to combined cue arrays did not confirm these predictions. In blocks where participants searched for large targets, behavioral spatial cueing effects and N2pc components were triggered by gap cues when a red singleton was present on the opposite side, as would be expected. In fact, these effects were equal in size to the effects observed for gap cues that appeared without a red singleton, which provides additional evidence that these color singletons were effectively excluded from attentional processing when size was the target-defining dimension. However, and critically, it was the red singletons and not the gap cues that triggered attentional capture in combined arrays when participants searched for red targets. RTs were fastest for targets at locations previously occupied by red singleton cues, whereas RTs to targets at gap cue locations were slower and did not differ from RTs to targets at the remaining uncued locations. Furthermore, an N2pc was elicited contralateral to the location of the red singleton cue, in spite of the fact that a gap cue was simultaneously present in the opposite hemifield. If gap cues in combined cue arrays had captured attention in a task-set-independent fashion because of their high bottom-up salience, this should have been reflected in behavioral spatial cueing effects and N2pc components in response to these cues even when color was task relevant and a competing color singleton was simultaneously present in the cue array. The fact that attentional capture effects were found for the location of red singleton cues in the color task demonstrates that capture was not driven by bottom-up salience. Instead, the color-specific top-down task set resolved attentional competition between the two singletons in favor of the task-set-matching stimulus. It should, however, be noted that behavioral spatial cueing effects triggered by red singleton cues in the color task tended to be smaller for combined cue arrays with gap cues on the opposite side than for arrays without gap cues, and N2pc amplitude to red singleton cues was reduced in combined cue arrays relative to cue arrays that only contained a red singleton. These observations suggest that a color-specific top-down task set did not completely eliminate attentional processing of gap cues in the opposite hemifield, which therefore retained some residual effect on attentional capture by the set-matching red singleton cues.

Before these findings can be interpreted as evidence for the partially task-set-independent nature of attentional capture by gap cues, two methodological concerns and one conceptual issue need to be addressed. First, it is important to note that task-set-independent behavioral spatial cueing effects in response to gap cues do not necessarily represent unequivocal evidence for bottom-up attentional capture. Because of the nature of these cue arrays, targets at cued locations are by definition targets that are presented at a previously unfilled position, whereas uncued targets are always preceded by a cue array item at the same position. Slower RTs for uncued targets could thus be due to sensory interactions between successively presented stimuli at the same location (e.g., forward masking), which might impair target detection or identification. If spatial cueing effects triggered by gap cues were simply an artifact of differential forward masking at cued versus uncued locations, faster RTs for targets preceded by gap cues at the same location should be present for combined cue arrays, even when participants search for color-defined targets. However, this was clearly not the case. For combined cue arrays in the color task, RTs to targets at the gap cue location did not differ from RTs to targets at a location previously occupied by a gray cue array item (Figure 2), demonstrating that low-level sensory interactions between cue and target arrays cannot account for the pattern of behavioral spatial cueing effects in response to gap cues.

A second methodological issue concerns the N2pc component as an online measure of attentional capture. Because this component is triggered prior to the arrival of subsequent target arrays, it is obviously not affected by sensory interactions between cue and target arrays. However, in order to interpret the N2pc as reflecting attentional capture by gap cues, it is important to rule out possible contributions of low-level visual asymmetries between hemifields that may result in lateralised ERP responses over visual cortical areas. For this reason, previous N2pc studies of attentional selectivity have been careful to employ fully balanced and symmetrical visual stimulus displays. This requirement is clearly not fully met by gap cue arrays, which by definition contain an unfilled position on the left or right side. Because these cue arrays were designed to study attentional capture by the absence of a stimulus, this type of sensory imbalance is inevitable but may result in asymmetric low-level sensory ERP responses. Indeed, gap cues triggered a small early asymmetry in the P1 time range (Figure 3), which raises the possibility that this asymmetry may also have affected the subsequent N2pc component. If the N2pc to gap cues does not reflect attentional capture but, instead, a lateralized visual ERP response at posterior electrodes that is caused by the asymmetrical structure of gap cue arrays, this low-level sensory ERP modulation contralateral to the side of a gap cue should also be present in combined cue arrays, regardless of top-down task set. This was not the case. As already discussed, the N2pc in response to combined cues in the color task was exclusively triggered contralateral to the side of the color singleton cue (Figure 3, bottom right panel), that is, there was no enhanced negativity contralateral to the location of the gap cue that could be attributed to the incompletely balanced nature of the cue array.

On a more conceptual level, one could also question our assumption that gap cues are coded as size-defined singletons (i.e., infinitesimally small stimuli). Alternatively, gap cues could be regarded as dimension-general singletons that represent the absence of any feature in any dimension at a specific location, that is, the zero value (or origin) for all stimulus dimensions. If this was the case, the observation that they attract attention both when color and when size is task relevant may not demonstrate strictly task-set-independent capture. Instead, it may reflect the dimension-general nature of gap cues, which implies that they are always partially task-set matching, regardless of which stimulus dimension is currently relevant.

In summary, the present findings provide important new insights into the control of attentional capture for different types of feature singletons. Color singletons capture attention only when they match a currently active feature-specific color task set, but not when another stimulus dimension is task-relevant. This is in line with the contingent involuntary attentional capture hypothesis postulated by Folk and colleagues (e.g., Folk et al., 1992), and demonstrates that capture by color singletons is not a bottom-up phenomenon, as is sometimes assumed (e.g., Theeuwes, 1991, 2010), but is instead under top-down control. In contrast, different principles apply to attentional capture by luminance discontinuities associated with the absence of an item in an otherwise regular stimulus array. This type of feature singleton will attract attention not only when relative stimulus size is task-relevant, but also when targets are defined in a different dimension (color). In marked contrast with the pattern of capture effects found for color singletons, this independence of attentional capture from currently active task sets may suggest salience-driven bottom-up control, but is also consistent with the view that gap cues are dimension-general singletons (see above). In any case, the ability of gap cues to capture attention is by no means absolute: When these cues are presented simultaneously with another task-set-matching color singleton in the opposite hemifield, attentional competition between these two items is rapidly decided in favor of the latter, resulting in attentional capture that is contingent on top-down search intentions.

Apart from their implication for models of attentional capture, the current ERP results are also relevant for the interpretation of the N2pc component. As this component is usually interpreted as a marker for the spatial selection of task-relevant visual stimuli, the observation that the N2pc can also be triggered by the *absence* of a stimulus is remarkable, as it strongly suggests that this selection process does not require a visual object to be physically present. This seems to suggest that the N2pc reflects the selection of spatial locations, rather than visual stimuli at specific locations. But this conclusion directly contradicts recent findings by Woodman, Arita, and Luck (2009), who demonstrated that the attentional process indexed by the N2pc is associated with the selection of visual objects (i.e., placeholders that mark cued target locations) rather than empty spatial locations. However, this contradiction may be more apparent than real. In the gap cues used in the present study, selected locations were not simply spatial coordinates in an empty visual field, but were instead characterized by the omission of a stimulus within an array of regularly spaced items. With these gap cue arrays, such contextually defined visual locations may have played a very similar role for attentional selection as the placeholder objects employed by Woodman et al. (2009).

Overall, the pattern of results obtained in this study indicates that the traditional dichotomy between purely stimulus-driven and fully task-set-contingent attentional capture may be an oversimplification and that important intermediate possibilities exist. Some salient items (such as color singletons) will only attract attention when they match current top-down task sets, regardless of whether they are the only singleton in the display or are presented together with another salient stimulus. Other salient stimuli (such as the gap cues used in this study) will attract attention in a task-set-independent fashion when they are the only unique display item, but not when they appear together with a competing set-matching singleton stimulus. In the former case, attentional capture is under full top-down control. In the latter case, capture is context dependent and is contingent on the absence of another task-set-matching event. However, neither represents purely stimulus-driven attentional capture, which is by definition not just independent of currently active top-down task sets, but should always be triggered by the most salient item in the display even when a competing set-matching stimulus is simultaneously present (e.g., Theeuwes, 1991, 1992). Even though the absence of an item in an orderly structured stimulus array is highly salient, it does not meet this second requirement. For this reason, the list of features that are able to capture attention in a bottom-up fashion will have to remain lamentably short.

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