Attentional capture by visual singletons is mediated by top-down task set: New evidence from the N2pc component

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Abstract

To investigate whether attentional capture by salient visual stimuli is mediated by current task sets, we measured the N2pc component as a marker of the spatial locus of visual attention during visual search. In each trial, a singleton stimulus that could either be a target (color task: red circle; shape task: green diamond) or a nontarget (blue circle or green square) was presented among uniform distractors (green circles). As predicted by the view that attentional capture is contingent on task set, the N2pc was strongly affected by task instructions. It was maximal for targets, attenuated but still reliably present for nontarget singletons defined in the target dimension (even when these were accompanied by an irrelevant-dimension singleton), and small or absent for equally-salient irrelevant-dimension singletons. Results demonstrate that attentional capture is not a purely bottom-up phenomenon, but is strongly determined by top-down task set.

Keywords: Attention, Attentional capture, Visual search, Pop-out, Cognitive control, Event-related potentials

Introduction

Selective attention is often used in a strategic and goal-directed fashion to bias perceptual and cognitive processing in favor of sensory events that are relevant to current intentions. While this intentional or endogenous mode of attentional selectivity is essential for the adaptive control of behavior, it is generally acknowledged that attention can also be attracted in an exogenous stimulus-driven fashion by certain types of salient events. Although this distinction between endogenous voluntary attentional selection and exogenous involuntary attention is often regarded as reflecting a fundamental difference between two distinct underlying attentional systems (e.g., Jonides, 1981; Müller & Rabbitt, 1989), the question under which conditions and by which stimuli exogenous attentional capture is elicited remains controversial.

One central and contentious issue is whether exogenous attentional capture is exclusively triggered in a stimulus-driven bottom-up fashion, or whether capture is also modulated by top-down attentional control settings. According to Theeuwes (e.g., 1994), attentional capture is linked to the low-level sensory properties of stimuli in the visual field, such that attention is rapidly captured by the most salient item in a bottom-up fashion, irrespective of current goals. While top-down task sets may determine whether or not attention is later withdrawn from such items (e.g., Theeuwes, Atchley, & Kramer, 2000), they cannot prevent attentional capture. This hypothesis is supported by the results of visual search studies in which a shape target was sometimes presented together with a more salient color singleton nontarget among perceptually uniform distractor items (e.g., Theeuwes, 1991). This color singleton delayed target detection, in spite of the fact that color was known to be task-irrelevant, suggesting that color singletons capture attention exogenously, independently of task instructions. In contrast, experiments by Folk and colleagues (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Folk & Remington, 1998) have suggested that attentional capture is mediated in a top-down fashion by current task sets. In these experiments, spatially uninformative peripheral cues preceded a visual search display that contained one salient target, and faster responses on trials where targets appeared at the cued location were interpreted as evidence of attentional capture by the cues. Critically, such spatial cuing effects were observed only for cues that matched the current task set. Color singleton cues produced cuing effects when targets were also color singletons, but not when targets were abrupt onset items. Cuing effects for onset cues were observed only for a task in which targets were also defined by abrupt onsets, but not when they were color singletons (cf. Folk et al., 1992).

Based on these results, Folk et al. (1992) proposed their contingent involuntary orienting hypothesis, according to which attentional capture by salient visual objects is not triggered in an automatic bottom-up fashion, but is contingent upon whether or not these objects match task-relevant attributes as defined in the current task set. However, this general version of their hypothesis does not define the level of specificity at which task set-dependent modulation of attentional capture can be found. It is possible that contingent capture operates exclusively at the level of *stimulus dimensions* (e.g., color, size, shape, orientation, etc.). In that case, searching for a red singleton target would prevent non-color singletons (such as a unique shape) from capturing attention, whereas nontarget color singletons (e.g., unique green or blue stimuli) would capture attention just as efficiently as red singletons. Alternatively, if contingent capture operates at the more specific level of *stimulus features* (e.g., red, green, blue, etc.), adopting a task set that defines targets as red singletons would prevent not only non-color singletons but also nontarget color singletons (e.g., a unique green item) from capturing attention.

Behavioral studies investigating this issue have produced mixed results. Folk et al. (1992, Exp. 4) found that green singleton color cues produced spatial cuing effects indicative of attentional capture even when observers searched for a red singleton target, and concluded that task-set contingent attentional capture was not determined at the level of specific features, but at a more general level of static versus dynamic discontinuities (see also Folk et al., 1994). However, another study by Folk and Remington (1998) found that attentional capture effects were only present when cue and target singletons shared the task-relevant feature (e.g., red), but not when singleton cues were defined by a nontarget color, in line with the hypothesis that contingent capture operates at the level of specific stimulus features. More recently, Lamy, Leber, and Egeth (2004) even found inverted spatial cuing effects for nontarget color singletons, suggesting active inhibition of singletons whose features do not match the currently active task set.

Overall, behavioral results remain inconclusive with respect to the question whether attentional capture is stimulus driven, as suggested by Theeuwes (1991, 1994), or is instead determined in a top-down fashion by feature- or dimension-specific task sets (as proposed by Folk and colleagues). In order to resolve this controversy, Bacon and Egeth (1994) suggested that task-set independent attentional capture by salient nontargets only occurs when observers adopt a singleton search strategy (i.e., a search for any discontinuity in the visual field rather than for a specific target attribute). Such a strategy is feasible under conditions where targets are always singleton items, as in the Theeuwes (1991) and Folk et al. (1992) studies, but fails when targets are not the only unique item in the visual field, as in the Folk and Remington (1998) and Lamy et al. (2004) studies. In this latter case, observers are forced to adopt a more specific feature search strategy, and task-set independent attentional capture is eliminated (see Bacon & Egeth, 1994, for more details).[1]

The aim of the present study was to use the N2pc component of the event-related potential (ERP) as a marker of spatially selective attentional processing to gain further insights into the impact of top-down task sets on attentional capture, and in particular into the relative roles of stimulus features and stimulus dimensions. The N2pc is defined as an enhanced negativity at posterior electrodes contralateral to the position of attended visual stimuli, typically emerges 200–300 ms after display onset, and is assumed to reflect the attentional selection of candidate target items among distractors in visual search tasks (Luck & Hillyard, 1994a, 1994b; Eimer, 1996; Girelli & Luck, 1997; Woodman & Luck, 1999; see also Brisson & Jolicœur, 2007a, 2007b, 2007c, 2007d; Dell'Acqua, Pesciarelli, Jolicœur, Eimer, & Peressotti, 2007; Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Eimer & Kiss, 2007; Eimer & Mazza, 2005; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, 2006b; Kiss et al., 2007; Kiss, Van Velzen, & Eimer, 2008; Mazza, Turatto, Umiltà, & Eimer, 2007; Robitaille & Jolicœur, 2006a, 2006b).

ERP studies that have employed the N2pc as an index of task-set dependent attentional capture have so far produced inconclusive results. Hickey, McDonald, and Theeuwes (2006) measured the N2pc to search displays that included a target shape singleton and a more salient nontarget color singleton, as in the study by Theeuwes (1991). An early N2pc to the nontarget color singleton preceded the N2pc elicited by the shape target, suggesting that color singletons captured attention, in spite of the fact that color was known to be task-irrelevant. This finding suggests that capture is primarily a bottom-up phenomenon, and therefore little affected by which target dimension or feature is specified by the currently active task set. In contrast, in another recent N2pc study that employed the spatial cuing procedure introduced by Folk et al. (1992), we (Eimer & Kiss, in press) found an N2pc to red color singleton cues in a task in which subsequent singleton targets were defined by the same color value (red), but not under conditions in which targets were abrupt onset items or size singletons. This pattern of results suggests that attentional capture by color singletons only occurs when the color dimension is currently task-relevant, in line with the contingent involuntary orienting hypothesis by Folk et al. (1992). No nontarget color singleton cues were presented in this study, thus leaving open the question of whether task-set contingent capture operates more specifically at the level of stimulus features. This question was addressed in another recent N2pc study by Leblanc, Prime, and Jolicœur (2008), who used a rapid serial visual presentation (RSVP) stream in which a central target was defined by a specific color, while peripheral stimuli could be ignored. An N2pc was triggered by peripheral irrelevant color singletons that shared the target color, but not for peripheral nontarget color singletons, suggesting that task-set dependent attentional capture is determined at the level of specific feature values (see also Folk, Leber, & Egeth, 2002; Leblanc & Jolicœur, 2005; and Nieuwenstein, 2006, for related behavioral results).

While these recent ERP studies have investigated attentional capture with relatively complex procedures such as the additional singleton paradigm (Hickey et al., 2006), spatial cuing (Eimer & Kiss, in press), and RSVP (Leblanc et al., 2008), effects of task set on capture can also be studied by measuring the N2pc to simple pop-out visual search displays that contain only one singleton item among uniform distractors, under different task instructions. This approach was adopted in several earlier studies (Luck & Hillyard, 1994a, 1994b; Girelli & Luck, 1997) that investigated attentional capture by color, orientation, size, or motion singletons under conditions where one of these dimensions was task-relevant. While the N2pc was clearly present in response to singletons defined within the current target dimension, it was small or absent for task-irrelevant dimension singletons, thus suggesting that task sets determine attentional capture at least at the level of stimulus dimensions. The only exception to this general pattern was found for motion singletons (Girelli & Luck, 1997), which triggered an N2pc even when participants were searching for color or orientation targets, suggesting that motion discontinuities may capture attention in a task-set independent bottom-up fashion. Along similar lines, Schubö, Schröger, Meinecke, and Müller (2007) have recently shown that no N2pc is triggered in response to task-irrelevant peripheral color and orientation pop-out stimuli when observers are instructed to respond to centrally presented target circles, demonstrating that unattended and task-irrelevant singletons do not capture attention.

In summary, existing behavioral and electrophysiological experiments have not yet provided conclusive evidence as to whether and when attentional capture is triggered by salient visual nontarget stimuli, and whether and how attentional capture is determined or modulated by the currently active task set. In the present study, these issues were investigated more systematically by measuring the N2pc component as a marker of attentional capture in response to color and shape target singletons, nontarget singletons that matched the target-defining dimension (color or shape) but not the target-defining feature, and nontarget singletons defined in the irrelevant dimension (color in the shape task, or shape in the color task). In Experiment 1, circular visual search arrays were presented that contained one singleton item presented against a background of perceptually uniform distractors (green circles). Singletons appeared with equal probability at one out of ten positions on the left or right side, but never at the top or bottom positions (see Figure 1). In the *color task,* participants were instructed to detect and respond to a red circle (target color singleton). In the *shape task*, they had to respond to a green diamond (target shape singleton). Target singletons were presented on one third of all trials. In the remaining trials, one of two nontarget singleton items (a blue circle or a green square) was presented with equal probability, and no response was required. Thus, although these nontarget singletons were physically identical in both tasks, they differed with respect to their association with the currently active task set. Nontarget color singletons (blue circles) matched the target-defining dimension in the color task, but not in the shape task, whereas the reverse was the case for nontarget shape singletons (green squares).

We compared the N2pc for singleton targets, relevant-dimension nontargets, and irrelevant-dimension nontargets, separately for color and shape singletons, in order to decide among alternative hypotheses about the nature of attentional capture, as reflected by this component. According to the hypothesis put forward by Theeuwes (1991, 1994) that capture is a purely bottom-up phenomenon that is triggered by stimulus salience irrespective of task set, there should be no systematic differences in N2pc components in response to targets, relevant-dimension nontargets, and irrelevant-dimension nontargets. Any N2pc differences observed in the present study should be solely attributable to bottom-up saliency differences between physically different singletons (e.g., color versus shape singletons). In contrast, the contingent involuntary orienting hypothesis predicts that N2pc components will differ systematically between the three singleton stimulus categories. According to a dimension-specific but feature-unspecific version of this hypothesis (that was suggested by the behavioral results of Folk et al., 1992, Exp. 4), attentional capture should be triggered by nontarget singletons that match the currently relevant stimulus dimension (color or shape), but not by singletons defined in a different dimension. Thus, while an N2pc should be present for relevant-dimension nontargets, this component should not be elicited in response to irrelevant-dimension nontargets (as observed previously by Luck & Hillyard, 1994a, 1994b, and Girelli & Luck, 1997). According to a stronger feature-specific version of task-set contingent attentional capture (and in line with the behavioral results of Folk et al., 1998, and

Lamy et al., 2005), no capture should be triggered by singleton stimuli that do not match the target-defining feature (red in the color task, and diamond-shaped in the shape task). In this case, the N2pc should be absent in response to either type of nontarget singleton, and should only be found for target singletons.

Experiment 1

Method

Participants. Fifteen paid volunteers participated in this experiment. Three of them were excluded because they failed to maintain eye fixation during the trials (see EEG data analysis). The remaining 12 participants (6 men, mean age 27.4 years) were right-handed and had normal or corrected-to-normal vision. Written consent was obtained from all participants. The experiment (as well as Experiments 2 and 3) was approved by the local ethics committee, and was conducted following the guidelines of the Helsinki declaration.

Stimuli. Stimuli were presented on a 17-inch computer monitor at a viewing distance of 70 cm against a black background. A light grey fixation point (CIE 1931 x/y coordinates: .318/.336; luminance = 65.1 cd/m^2) was continuously visible throughout each block. Search displays consisted of twelve stimulus elements presented at equidistant positions from central fixation (4.5° visual angle) along the circumference of a virtual circle centered on the fixation point (see Figure 1). In each trial, the display contained eleven identical distractors (green circles) presented together with one singleton item (a red or blue circle, or a green square or diamond). These singletons were never presented at the top or bottom positions of the virtual circle. CIE 1931 x/y coordinates for the three colors were .276/ .412 (green), .408/.366 (red), and .221/.238 (blue), and all three colors were approximately equiluminant (luminance values 13.7 cd/m^2; 14.1 cd/m^2; and 14.2 cd/m^2 for green, red, and blue). Circles, diamonds, and squares all subtended approximately 1.1° visual angle in diameter.

Procedure. Participants performed two tasks, each presented in eight successive experimental blocks with 90 trials per block (resulting in a total of 720 trials per task), with task order counterbalanced. They had to detect a pre-specified target singleton stimulus (a red circle in the color task, and a green diamond in the shape task, see Figure 1), and to press a left or right response key with the index or middle fingers of their right hand when this target was presented to the left or right of fixation, respectively. Target singletons were presented on 30 trials per block, and with equal probability at one of the ten lateral positions to the left or right of fixation (but never at the top or bottom). No responses were required on the remaining randomly intermingled 60 trials per block in which a nontarget singleton was presented instead. In both tasks, 30 trials contained a nontarget color singleton (a blue circle), and 30 trials contained a nontarget shape singleton (a green square) presented randomly at one of the ten lateral positions.

Each search array was presented for 150 ms, and the stimulus onset asynchrony between successive search arrays was 2000 ms. Participants were instructed to keep central fixation throughout each trial, and to respond to singleton target stimuli only as fast and accurate as possible. On trials with response errors, visual feedback ("Incorrect" or "No response") was given after 1500 ms.

EEG recording and data analysis. The EEG was DC-recorded with a lowpass of 40 Hz and a sampling rate of 200 Hz from 23 Ag-AgCl electrodes mounted in an elastic cap according to the extended International 10-20 system at Fpz, F7, F3, Fz, F4, F8, FC5, FC6, T7, C3, Cz, C4, T8, CP5, CP6, P7, P3, Pz, P4, P8, PO7, PO8, and Oz. Scalp electrodes were referenced to linked earlobes. Horizontal eye movements (HEOG) were measured bipolarly from a pair of electrodes placed at the outer canthi of the eyes. All electrode impedances were kept below 5 kΩ.

The EEG was epoched from 100 ms prior to 500 ms after the onset of the search display. Epochs containing blinks (Fpz exceeding ±60 μV), horizontal eye movements (HEOG ±25 μV) or movement artifacts (±80 μV at all other electrodes) were eliminated from further analyses. To ensure that lateralized EEG activity obtained at posterior electrodes was not contaminated by saccades to the singleton, three participants with an HEOG after artifact rejection larger than ±3 μV in at least one experimental condition were excluded from analyses. ERPs were averaged for each combination of task (color, shape), singleton type (target, color nontarget, shape nontarget) and singleton position (left, right).

The N2pc was quantified on the basis of mean amplitudes obtained at lateral posterior electrodes PO7/PO8 between 200 and 280 ms after search array onset. To verify the presence of an N2pc to target stimuli (red circles in the color task, and green diamonds in the shape task), mean amplitude values in response to these stimuli were analysed with repeated-measures analyses of variance (ANOVAs) for the factors singleton side (left vs. right) and contralaterality (contralateral vs. ipsilateral hemisphere relative to the side of the singleton). Then, two additional sets of analyses were conducted. First, in order to investigate task-set induced differences in attentional capture at the level of features, ERPs to singleton targets and to nontarget singletons defined within the target dimension (i.e., blue circles in the color task, and green squares in the shape task) were compared separately for both tasks with ANOVAs including the factors singleton type (target vs. relevant-dimension nontarget), singleton side, and contralaterality. Second, in order to investigate task-set induced differences in attentional capture at the level of stimulus dimensions, ERPs to physically identical nontarget singletons (blue circles and green squares) obtained in both tasks were analyzed separately for both singleton types, with the factors task (color vs. shape), singleton side, and contralaterality. Additional analyses were also conducted for each of the four combinations of nontarget singleton stimulus type (color vs. shape) and task (color vs. shape) in order to substantiate the presence or absence of the N2pc in each of these conditions. Effect sizes are reported as partial eta squared (η_p^2) for all significant ERP effects.

Results

Behavioral performance. Correct responses to target singletons were faster in the color task than in the shape task (466 vs. 538 ms; $t(11) = 9.5$, $p < .001$). Accuracy was at ceiling for both target types, with more than 99% trials correct in both tasks.

N2pc to singleton stimuli. Figure 2 shows ERP waveforms elicited at posterior electrodes PO7/8 contralateral and ipsilateral to the visual field where color singletons (left side) and shape singletons (right side) were presented. The top panels show that large N2pc components were triggered in response to both target singletons (red circles in the color task, and green diamonds in the shape task), and this was reflected by significant main effects of contralaterality, $F(1,11) = 111.2$ and 65.9, for color and shape targets, respectively, both $p < .001$, $\eta_p^2 = .91$ and .86, respectively.

The middle panels suggest that an N2pc was also triggered in response to nontarget singletons (blue circles and green squares) when the respective singleton dimension matched the current task set (i.e., blue circles in the color task, and green squares in the shape task), but that its amplitude was attenuated relative to the N2pc observed in response to target singletons. This latter observation was confirmed by interactions between singleton type (target vs. nontarget) and contralaterality in the analyses conducted separately for both tasks, $F(1,11) = 93.5$, $p < .001$, $\eta_p^2 = .89$, for target versus nontarget color singletons in the color task; $F(1,11) = 13.7$, $p < .003$, $\eta_p^2 = .56$, for target versus nontarget shape singletons in the shape task. However, follow-up analyses confirmed that a significant N2pc was triggered in response to nontarget color singletons in the color task, $F(1,11) = 40.3$, $p < .001$, $\eta_p^2 = .79$, as well as to nontarget shape singletons in the shape task, $F(1,11) = 59.2$, $p < .001$, $\eta_p^2 = .84$, demonstrating that although the N2pc was attenuated to nontarget singletons defined within the currently relevant dimension, it was still reliably present.

Figure 2 (bottom panels) shows ERP waveforms to nontarget color and shape singletons when the singleton dimension did not match the current task set (i.e., blue circles in the shape task, and green squares in the color task). The N2pc was strongly attenuated relative to the N2pc observed in response to physically identical nontarget stimuli that matched the current task dimension (Figure 2, middle panels). This difference was substantiated by analyses conducted for these nontarget singletons across both task sets, separately for color and shape singletons, which revealed interactions between task set and contralaterality for nontarget color singletons, $F(1,11) = 42.9$. $p < .001$, $\eta_p^2 = .80$, as well as for nontarget shape singletons, $F(1,11) = 50.0$. $p < .001$, $\eta_p^2 = .82$. In follow-up analyses, the N2pc to nontarget color singletons only approached statistical significance in the shape task, $F(1,11) = 3.5$, $p = .089$, $\eta_p^2 = .24$. In contrast, a reliable N2pc was still present for nontarget shapes in the color task, $F(1,11) = 13.5$, $p < .01$, $\eta_p^2 = .55$.

Discussion of Experiment 1

Experiment 1 demonstrated that the task relevance of the features and dimensions of singleton items in a visual search display strongly affects their capacity to capture attention, as reflected by the N2pc component. As expected, a large N2pc was obtained in response to color and shape target singletons, indicating capture of attention by singleton stimuli that match the current task set. For nontarget singletons defined in the target dimension (blue circles for the color task, green squares for the shape task), a highly significant N2pc was also triggered in both tasks, strongly suggesting that these stimuli captured attention on a substantial number of trials, in spite of the fact that they lacked the target-defining feature (red or diamond-shape). If task-set contingent attentional capture operated exclusively on the level of specific feature values, as postulated by a strong version of the contingent involuntary orienting hypothesis, these stimuli should not have attracted attention, and therefore should not have triggered an N2pc. Thus, the fact that reliable N2pc components were observed for these stimuli in Experiment 1 appears inconsistent with the view that contingent attentional capture is solely mediated by feature-specific task sets.

It should be noted, however, that even though an N2pc was clearly present to relevant-dimension color and shape nontargets, it was attenuated as compared to the N2pc triggered in response to color and shape targets. This observation suggests that although feature-specific task sets did not prevent attentional capture, they did modulate the degree to which singleton stimuli were able to attract attention. If one assumes that attention was attracted by target singletons on virtually every target-present trial, the reduction of N2pc amplitudes to relevant-dimension nontarget singletons (without substantial latency difference, see Figure 2) indicates that these stimuli failed to capture attention on a substantial number of trials. This seems inconsistent with the hypothesis that attentional capture is solely determined by bottom-up stimulus salience, since it suggests that feature-specific task sets will often prevent capture by nonmatching singletons.

The fact that the N2pc was larger for shape nontarget singletons in the shape task than for color nontarget singletons in the color task (see Figure 2) is likely due to the fact that in spite of our efforts to equate the physical difference between targets and nontargets across both tasks, the discrimination between shape targets and nontargets was still more difficult than the discrimination between color targets and nontargets, resulting in slower RTs for shape targets in the shape task than for color targets in the color task. If shape nontargets were perceptually more similar to shape targets than color nontargets were to color targets, the former would have captured attention more frequently, thus resulting in larger N2pc amplitudes.

For irrelevant-dimension nontarget singletons (blue circles in the shape task, green squares in the color task), the N2pc was much smaller as compared to when the same stimuli matched the task-relevant dimension. This observation clearly demonstrates a top-down modulation of attentional capture that is contingent on the current target dimension, and is therefore at odds with the view that capture is exclusively based on bottom-up salience, which would predict identical N2pc components regardless of whether participants were instructed to detect a color or a shape target. The fact that, albeit strongly attenuated, the N2pc to irrelevant-dimension nontargets was still significant for shape singletons in the color task, and approached significance for color singletons in the shape task, suggests that these stimuli did attract attention on at least some trials, and thus indicates some task-set independent role for bottom-up saliency.

In summary, the results of Experiment 1 provide clear support for the contingent involuntary orienting hypothesis. The N2pc as a marker for attentional capture by singleton stimuli was strongly affected by task set, even when search arrays were physically identical.

The fact that N2pc amplitudes were largest for targets, intermediate for relevant-dimension nontargets, and strongly attenuated for irrelevant-dimension nontargets suggests that capture is not an all-or-nothing phenomenon, but that it is instead mediated in a gradual fashion by both feature-specific and dimension-specific task sets. This possibility will be further considered in the General Discussion.

One could argue that because target and nontarget singletons were both presented unpredictably at the same lateral locations, nontargets were by definition always located at a potentially task-relevant location, and this may have made them more likely to capture attention than under conditions where their position was always irrelevant. Therefore, the N2pc results observed in Experiment 1 may not be representative of the degree of attentional capture that is elicited by nontarget singletons at task-irrelevant locations. Experiment 2 was conducted to further investigate this issue.

Experiment 2

In Experiment 2, the positions where nontarget singletons could appear were task-irrelevant throughout, because color and shape targets, when present, were now only delivered at the top or bottom locations (12 and 6 o'clock positions on the virtual circle). In contrast, nontarget singletons were always presented at lateralized positions in the left or right visual field, so that the N2pc could be computed for these stimuli. If the N2pc observed in response to nontarget singleton stimuli in Experiment 1 was primarily due to the fact that these stimuli were always presented at potentially task-relevant locations, no N2pc should be elicited by nontargets in Experiment 2.

Method

Participants. Thirteen volunteers took part in this experiment. Data from one participant was discarded because of excessive alpha activity. The remaining 12 participants (3 men, mean age 24 years) were all right-handed and had normal or corrected-to-normal vision.

Stimuli and procedure. The general procedure was the same as in Experiment 1, with the following exceptions. In Experiment 2, target singletons could appear only on the vertical meridian, either at the 6 o'clock or at the 12 o'clock position of the circular array. Thus, all ten lateral positions where nontarget singletons could appear were task-irrelevant throughout the experiment.

EEG recording and data analysis. All recording and analysis procedures were the same as in Experiment 1. Because the N2pc is a lateralized response to visual events in the left or right hemifield, this component could not be measured to target singletons, which always appeared on the vertical meridian. Therefore, analyses focused on the impact of task set on N2pc components triggered by nontarget color or shape singletons. To investigate the presence or absence of the N2pc for each of the four combinations of nontarget singleton type (color vs. shape) and task, separate ANOVAs were conducted on ERP mean amplitudes obtained in the 200–280 ms post-stimulus interval for each of these conditions, including the factor contralaterality (contralateral vs. ipsilateral hemisphere relative to the side of the singleton). In addition, further ANOVAs were conducted separately for color and shape singletons, using the factors task (color vs. shape), singleton side (left vs. right) and contralaterality.

Results

Behavioral performance. In contrast to Experiment 1, correct response times to target singletons did not differ across tasks (497 vs. 500 ms, for the color and shape tasks, respectively, $t < 1$). Error rates were again below 1% for both tasks.

N2pc to nontarget singleton stimuli. Figure 3 shows ERP waveforms elicited at posterior electrodes PO7/8 contralateral and ipsilateral to the visual field where nontarget color singletons (left side) and nontarget shape singletons (right side) were presented. Nontarget color singletons elicited a small but robust N2pc in the color task (main effect of contralaterality: $F(1,11) = 5.3$, $p < .05$, $\eta_p^2 = .32$), while no evidence for an N2pc to the same nontarget color singletons was found in the shape task ($F < 1$). This impact of top-down task set on the N2pc component to nontarget color singletons was also reflected by a significant task x contralaterality interaction, $F(1,11) = 7.8$, $p < .02$, $\eta_p^2 = .41$, in the overall ANOVA. A similar pattern was found for nontarget shape singletons. In the shape task, a reliable N2pc was elicited in response to these stimuli (main effect of contralaterality: $F(1,11) = 17.7$, $p < .001$, $\eta_p^2 = .62$), while the N2pc was absent in response to physically identical singletons in the color task, $F < 1$. This pattern was again reflected by a significant task x contralaterality interaction in the overall ANOVA, $F(1,11) = 24.1$, $p < .01$, $\eta_p^2 = .69$.

Comparison of N2pc amplitudes across Experiments 1 and 2. Visual inspection of the ERP waveforms obtained in Experiments 1 and 2 (see Figures 2 and 3) suggests that N2pc amplitudes elicited by nontarget singletons in Experiment 2 (in which the locations occupied by these singletons were task-irrelevant throughout) were reduced relative to N2pc amplitudes obtained for physically identical displays in Experiment 1 (in which these locations were task-relevant). This difference was further explored by additional ANOVAs on the pooled N2pc data across Experiments 1 and 2 with experiment as additional factor. These analyses were conducted only for nontarget singletons that matched the current task set, as reliable N2pc components were observed for these stimuli in both experiments. A significant experiment x contralaterality interaction, $F(1,22) = 13.1$, $p < .002$, $\eta_p^2 = .37$, confirmed that N2pc amplitudes in response to these stimuli were attenuated in Experiment 2. In addition, a three-way interaction (task x experiment x contralaterality: $F(1,22) = 10.3$, $p < .004$, $\eta_p^2 = .32$) was obtained, due to the fact that this attenuation was more pronounced for nontarget shape singletons in the shape task than for color singletons in the color task. However, follow-up ANOVAs computed separately for color and shape singletons revealed experiment x contralaterality interactions for both singleton types, $F(1,22) = 4.9$, $p < .04$, $\eta_p^2 = .18$, and $F(1,22) = 16.6$, $p < .001$, $\eta_p^2 = .43$, for color and shape singletons, respectively, thus confirming that the attenuation of N2pc amplitudes in Experiment 2 relative to Experiment 1 was reliably present for both tasks.

Discussion of Experiment 2

The results obtained in Experiment 2 were clear-cut. When target singletons were only presented at the top or bottom positions, and the positions occupied by nontarget singletons were therefore always task-irrelevant, reliable N2pc components were still triggered in both tasks by nontarget singletons defined in the same dimension as the current target. This finding implies that such nontarget singletons can capture attention even when presented at spatial locations that are known to be irrelevant (cf. Leblanc et al., 2008, who also found an N2pc to distractor stimuli at task-irrelevant peripheral locations), and therefore provides strong evidence against the view that task-set contingent attentional capture operates exclusively on the feature-specific level. If that was the case, no N2pc to nontargets should have been triggered at all in Experiment 2.

Given the presence of an N2pc for relevant-dimension nontargets, the finding that the N2pc was entirely absent when the dimension of these nontargets did not match the current target dimension is especially relevant, as it further underlines the important role of target dimensions for task-set contingent attentional capture that was already evident in Experiment 1. The fact that the N2pc to irrelevant-dimension singletons was small but significant (or nearly significant, for color singletons) in Experiment 1, but entirely absent in Experiment 2, is likely due to the difference in the task relevance of nontarget positions between experiments. This interpretation is further supported by the fact that even for relevant-dimension nontarget singletons, N2pc amplitudes were significantly attenuated for both tasks in Experiment 2 relative to Experiment 1. These findings indicate that the ability of nontarget singletons to capture attention in Experiment 1 was enhanced by the fact that they were presented at potentially task-relevant locations. The N2pc results obtained in Experiment 2 may therefore provide a more conservative measure of their capacity for attentional capture.

In contrast to Experiment 1, where RTs to shape targets were considerably slower than RTs to color targets, no such RT difference was observed in Experiment 2. This is likely to be due to the more focused state of attention in Experiment 2 where targets could appear in only two rather than ten different locations, as in Experiment 1. If the discrimination between shape targets and nontargets was more difficult than the discrimination between color targets and nontargets, the detection of shape target stimuli should benefit most when attention is more narrowly focused, resulting in faster RTs.

In summary, Experiment 2 has provided further evidence for task-set contingent capture of attention. The observation that physically identical nontarget singletons trigger an N2pc when they are defined within the currently relevant dimension (color or shape), but not when their dimension is task-irrelevant, is clearly inconsistent with the hypothesis that attentional capture, as reflected by the N2pc, is solely determined by bottom-up salience differences. However, one could still argue that results obtained with the search arrays used in Experiments 1 and 2 (nonbalanced displays containing a unique salient singleton on one side among uniform distractors) cannot be easily applied to more complex stimulus conditions, such as the additional singleton paradigm (Theeuwes, 1991; Hickey et al., 2006), in which two singletons items are presented concurrently. Experiment 3 was conducted to provide further evidence for task-set contingent attentional capture under conditions where visual search arrays contain two salient singleton items (one in each hemifield) that will compete for attentional selection.

Experiment 3

Experiment 2 has demonstrated that an N2pc to nontarget singletons at task-irrelevant locations is triggered only when these singletons are defined in the current task dimension (color or shape), indicative of task-set contingent attentional capture. Experiment 3 investigated whether the N2pc is still determined by task set under conditions where color and shape nontarget singletons are presented simultaneously. As in Experiment 2, color or shape target singletons were presented at the top or bottom positions only, and therefore no N2pc could be obtained for these stimuli. In contrast to Experiment 2, each nontarget trial now contained both nontarget singletons (blue circle and green square), which were presented on diagonally opposite positions on the left and right side (see Figure 1, bottom panel). Thus, while nontarget stimulus arrays were always symmetrical with respect to the location of the two singletons, and physically identical in both tasks, only one of these nontarget singletons matched the currently active task dimension, while the other was from the task-irrelevant dimension. Task-set contingent attentional capture should be reflected by an N2pc of opposite polarity for nontarget search arrays in the two tasks. In the color task, an N2pc should be triggered contralateral to the location of the nontarget color singleton (i.e., ipsilateral to the shape singleton). In the shape task, an N2pc should instead be observed contralateral to the location of nontarget shape singleton (i.e., ipsilateral to the color singleton).

Method

Participants. Fourteen volunteers took part in this experiment. Two of them were excluded from further analyses due to excessive eye movements and alpha activity. The remaining 12 participants (6 men, mean age 27.1 years) had normal or corrected-to-normal vision and all but one were right-handed.

Stimuli and procedure. Stimuli and procedure were identical to Experiment 2 with the following exceptions. Nontarget trials now always contained both nontarget singletons (a blue circle and a green square) among ten distractor items (green circles). These two stimuli appeared with equal probability and randomly at any of the ten lateral positions, with the constraint that they were always presented at diametrically opposite positions of the circular array (see Figure 1, bottom, for an example). As in Experiments 1 and 2, each block contained 30 target trials and 60 nontarget trials.

EEG recording and data analysis. EEG recording procedures were identical to Experiments 1 and 2. The N2pc was quantified only for nontarget stimulus arrays, as in Experiment 2, as target singletons were always presented on the vertical meridian. ANOVAs were conducted for ERP mean amplitudes obtained in the 200–280 ms post-stimulus interval, separately for the color and shape tasks, for the factors singleton side (left vs. right) and contralaterality (contralateral vs. ipsilateral hemisphere). Note that this contralaterality factor was now defined with respect to the side of the singleton that matched the currently active task set (i.e., the side of the blue circle in the color task, and the side of the green square for the shape task).

Results

Behavioral performance. Correct response times to singleton targets were slightly but significantly faster in the color task as compared to the shape task (453 vs. 477 ms, respectively; $t(11) = 2.7$, $p < .02$). As in the previous two experiments, error rates were below 1% for both tasks.

N2pc to nontarget arrays with bilateral singletons. Figure 4 shows ERP waveforms obtained at PO7/8 in response to nontarget arrays that contained one singleton stimulus on either side (a blue circle on the left and a green square on the right, or vice versa), separately for the color task (left panel) and the shape task (right panel). In these plots, ERPs triggered at electrodes contralateral to the singleton that matches the target dimension (color or shape) are indicated with solid lines, while ERPs contralateral to the nonmatching singleton are shown as dashed lines. Although these displays were in fact physically identical, the polarity of the effects obtained in the N2pc time interval appear to be determined by top-down task set, with an enhanced negativity emerging contralateral to the location of the singleton item that matches the currently active task set.

This was confirmed by statistical analyses, which revealed a significant effect of contralaterality in the color task, $F(1,11) = 14.6$, $p < .003$, $\eta_p^2 = .57$, reflecting an N2pc elicited contralateral to the side of the nontarget color singleton (blue circle), as well as a main effect of contralaterality in the shape task, $F(1,11) = 5.9$, $p < .03$, $\eta_p^2 = .35$, now reflecting an N2pc contralateral to the side of the nontarget shape singleton (green square). When the N2pc data from both tasks were analyzed together, with task as additional factor, no evidence for any task x contralaterality interaction was obtained, $F < 1$, confirming that the N2pc effects shown in Figure 4 were equivalent in size for both tasks.

Comparison of N2pc amplitudes across Experiments 2 and 3. To find out whether the presence of an additional singleton in the task-irrelevant dimension in Experiment 3 had any effect on N2pc amplitudes in response to nontarget singletons in the relevant dimension, N2pc results from Experiment 3 were compared to the analogous results from Experiment 2 for trials where these singletons were presented without an additional contralateral singleton in an ANOVA with experiment as additional factor. For relevant-dimension nontarget color singletons in the color task, there was a main effect of contralaterality, $F(1,22) = 14.1$, $p < .001$, $\eta_p^2 = .39$, but no experiment x contralaterality interaction, $F < 1$, suggesting that the presence of an additional singleton did not affect N2pc amplitudes to these stimuli. Likewise, for relevant-dimension nontarget shape singletons in the shape task, the main effect of contralaterality, $F(1,22) = 21.6$, $p < .001$, $\eta_p^2 = .49$, was not accompanied by a significant experiment x contralaterality interaction, $F < 1.2$.

Discussion of Experiment 3

The results obtained in Experiment 3 were exactly in line with the predictions of the task-set contingent attentional capture hypothesis. When nontarget color and shape singletons were presented simultaneously on opposite sides of the search arrays, an N2pc was triggered contralateral to the color singleton in the color task, and contralateral to the shape singleton in the shape task. Because nontarget displays were physically identical, and balanced with respect to the position of the two singletons, this polarity reversal of the N2pc cannot be explained with respect to differences in bottom-up stimulus salience, and thus provides additional evidence in favor of a top-down modulation of attentional capture by currently active task sets. It suggests that attention is captured by whatever nontarget singleton matches the target-defining dimension. Moreover, the N2pc obtained in response to relevant-dimension color and shape nontarget singletons in Experiment 3 did not differ statistically from the N2pc triggered by these stimuli in Experiment 2 where no competing singleton stimulus was present. This strongly suggests that top-down effects of task set on attentional capture are not restricted to one-singleton search arrays, but are also elicited in a similar fashion in response to search displays that contain more than one singleton item.

General Discussion

The results obtained in these three experiments provide new electrophysiological evidence for task-set contingent attentional capture (Folk et al., 1992). We measured the N2pc component as a marker of attentional capture by singleton stimuli in visual search displays, and found that the N2pc was strongly affected by task sets, both at the level of specific stimulus features (Experiment 1), as well as at the level of stimulus dimensions (all three experiments). In Experiment 1, N2pc amplitudes were larger for color and shape targets than for nontarget singletons that matched the target dimension but not the target-defining feature, thus demonstrating that attentional capture was modulated in a feature-specific fashion by the current task set. However, the observation that reliable N2pc components were still present for relevant-dimension nontarget singletons strongly suggests that contingent capture is not exclusively mediated at the feature level. This was further confirmed in Experiments 2 and 3, where nontarget singletons defined in the relevant dimension (color or shape) triggered significant N2pc components, in spite of the fact that their locations were now task-irrelevant, and the fact that they were accompanied by irrelevant-dimension nontarget singletons on the opposite side (in Experiment 3).

The fact that an N2pc was triggered in Experiment 2 in response to nontarget singletons defined within the currently relevant dimension, but not for physically identical irrelevant-dimension singletons, suggests that task-set contingent attentional capture also operates at the level of stimulus dimensions. This conclusion was further supported by the demonstration of Experiment 3 that the polarity of the N2pc in response to search arrays containing a nontarget singleton on either side was determined by which of these singletons matches the current target dimension. The fact that a small residual N2pc was observed in response to irrelevant-dimension nontargets in Experiment 1 is likely due to the fact that these stimuli were presented at potentially task-relevant locations.

The aim of the present study was to decide among alternative hypotheses with respect to the nature of attentional capture by salient singleton stimuli in visual search displays, as reflected by the N2pc component. According to the hypothesis that capture is triggered exclusively by bottom-up stimulus salience irrespective of task set (Theeuwes, 1991, 1994), there should have been no systematic differences in N2pc components in response to target and nontargets, and in particular between relevant-dimension and irrelevant-dimension nontarget singleton arrays, as these were physically identical. The fact that all three experiments revealed strong effects of task set on N2pc amplitudes is clearly inconsistent with this hypothesis, and more generally with any account that regards bottom-up salience as the main driving force of attentional capture. For example, one could argue that because targets were always singleton items in the current study, participants may have adopted a generalized singleton search mode (as defined by Bacon & Egeth, 1994). If this had been the case, all singleton stimuli should have captured attention in a similar fashion, regardless of current task instructions, which was clearly not the case.

Alternatively, a strong feature-specific version of the task-set contingent capture hypothesis postulates that capture is mediated exclusively at the feature level, and that singletons lacking the target-defining feature (e.g., redness or diamond shape) will not capture attention (as suggested by the behavioral results of Folk et al., 1998, and Lamy et al., 2005). The fact that reliable N2pc components were triggered in all three experiments to relevant-dimension nontarget singletons is clearly inconsistent with this hypothesis, since it implies that blue color singletons often captured attention when participants searched for a red target, as did square shape singletons when diamonds were targets. However, the fact that N2pc amplitudes were attenuated for these stimuli as compared to color and shape targets does suggest that capture is modulated (but not completely eliminated) at the level of feature-specific task sets. Finally, a dimension-specific but feature-unspecific version of task-set contingent attentional capture predicts that capture is triggered by nontarget singletons that match the currently relevant stimulus dimension (color or shape; as also suggested by the behavioral results of Folk et al., 1992, Exp. 4), but not by singletons defined in a different dimension. The fact that relevant-dimension nontarget singletons elicited an N2pc in all three experiments, whereas the N2pc to irrelevant-dimension singletons was strongly attenuated or entirely absent, and the observation that the polarity of the N2pc to nontarget singletons was determined by the currently task-relevant dimension (Experiment 3), are all very much in line with the predictions of this hypothesis. They are also consistent with results from previous ERP studies that have found little evidence for attentional capture by irrelevant-dimension nontarget singletons (Luck & Hillyard, 1994a, 1994b; Eimer & Kiss, in press; but see Girelli & Luck, 1997, for evidence that motion singletons may capture attention even when irrelevant).

This line of argument is based on the assumption that the N2pc to singleton items in visual search arrays primarily reflects the degree to which attention is captured by these stimuli. Alternatively, one could argue that the N2pc not just indicates attentional capture, but also the amount of attentional processing required by specific singleton items. For example, for displays containing one target and one nontarget item on opposite sides of the visual field, a larger N2pc has been observed during a difficult orientation discrimination task than during a simpler feature detection task (Luck, Girelli, McDermott, & Ford, 1997). Thus, the large N2pc to target items in the present study may be due to the fact that these stimuli are task-relevant and thus require in-depth processing, whereas the N2pc to nontarget singletons is attenuated because these stimuli are rapidly rejected from further processing once color or shape information has been extracted. According to this account, such N2pc modulations are not primarily due to task-set contingent attentional capture, but rather to differences in the degree of processing required by attended stimuli. However, a recent study that used multi-stimulus visual search displays similar to those employed here (Mazza et al., 2007) obtained results that are not in line with this alternative explanation. In this experiment, differences in attentional processing demands (localization versus identification of color singleton targets) did not affect the N2pc to these stimuli, suggesting that this component primarily reflects the initial attentional selection of targets rather than their subsequent in-depth attentional processing. More importantly, the results of Experiments 2 and 3 of the current study also appear inconsistent with such an alternative interpretation. In both experiments, an N2pc was elicited in response to relevant-dimension nontargets in spite of the fact that these stimuli were always presented at task-irrelevant locations. If the N2pc reflected endogenous attentional processing demands, no N2pc should have been present for stimuli that can be immediately rejected as nontargets on the basis of their location. In our view, the presence of an N2pc to relevant-dimension but not irrelevant-dimension nontargets in Experiments 2 and 3 underlines the limits of endogenous attentional control, and suggest that attention is captured in a task-set contingent fashion even when stimulus locations are known to be task-irrelevant.

According to the general hypothesis that attentional capture is mediated by top-down control settings, observers can flexibly opt for a search strategy that is best suited to the demands of a specific visual search task. Thus, capture is not an all-or-nothing phenomenon that is tightly linked to physical stimulus characteristics, but is instead mediated by context-specific top-down search modes. From this perspective, the fact that Leblanc et al. (2008) found no N2pc for peripheral color singleton distractors in a color task, whereas reliable N2pc components were obtained in all three experiments of the present study in response to relevant-dimension nontarget singletons, may not be all that surprising. In the Leblanc et al. study, where targets were accompanied in time or in space by same-dimension distractors, participants may have been forced into a search mode that was strongly focused on a particular feature value, rather than on any discontinuity in the relevant feature dimension. In the present study, targets were always singletons, and participants may therefore have chosen a less feature-specific search strategy, where they searched for any discontinuity in the relevant dimension.[2] In other words, the current N2pc results are consistent with the view that observers might have adopted a singleton search strategy (as defined by Bacon & Egeth, 1994) that was however restricted to the currently relevant stimulus dimension (color or form). This would enable them to filter out, effectively, salient singletons in the task-irrelevant dimension, but would cause capture by nontarget feature values in the task-relevant dimension. The fact that the N2pc was larger for targets than relevant-dimension nontargets (Experiment 1) suggests that even within such a dimension-specific singleton search mode, search was still biased in a top-down fashion toward the task-relevant stimulus feature.

While the present findings strongly support the task-set contingent attentional capture hypothesis, results from another recent ERP study that also employed the N2pc as a marker of capture (Hickey et al., 2006) have led to the conclusion that attentional capture is at least partially determined by bottom-up saliency. When a target shape singleton and a more salient nontarget color singleton were presented in opposite hemifields against a background of uniform distractors, a small but reliable N2pc was triggered by color singletons prior to the N2pc to the shape target, suggesting that attention was initially captured in a bottom-up fashion by the irrelevant color singleton. This finding contrasts markedly with the results obtained in the present Experiment 3, where search displays also contained two singletons, but the polarity of the N2pc was entirely determined by top-down task set. There are several procedural differences between these experiments that may account for these discrepant results. First, while the nontarget singletons were chosen to be more salient than target singletons in the Hickey et al. (2006) study, we tried to keep the salience of color and shape singletons as constant as possible. Thus, the results of Hickey et al. (2006) may suggest that large salience differences can override the impact of top-down task set on attentional capture. In addition, targets could appear at any location in the Hickey et al. (2006) study, whereas there were only two possible target positions in the present Experiment 3. Finally, because two different shape targets that changed unpredictably across trials were used by Hickey et al. (2006), top-down task sets may have been less precisely defined than in the current experiment where target singletons remained constant throughout the color and shape tasks (see also Pinto, Olivers, & Theeuwes, 2005, for recent behavioral evidence that attentional capture effects are stronger when target identity is uncertain). These issues clearly need to be addressed in future experiments.

In summary, the present N2pc study has demonstrated that attentional capture by color and shape singletons in visual search displays is strongly modulated by task set. Capture is attenuated although not eliminated for singleton stimuli that match the target dimension, but lack the target-defining features, and is almost completely absent for singletons defined in a currently task-irrelevant dimension. Top-down factors thus play a major role in determining whether and when salient visual stimuli are able to attract attention.

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Footnotes

[1] It is worth noting that in the Lamy et al. (2004) study, as well as in some conditions of the Folk & Remington (1998) study, color targets were nonsingletons, as they appeared among a heterogeneous set of color distractors. This was done in order to force participants into a feature search strategy, as defined by Bacon & Egeth (1994), and may thus account for the absence of any attentional capture effects for nontarget color singletons that had previously been observed by Folk et al. (1992).

[2] It should be noted that this discrepancy in the N2pc results reported by Leblanc et al. (2008) and the results obtained in the present study might also be linked to differences in the demands on spatial attention. In Experiments 1 to 3 of the Leblanc et al. study, participants had to monitor a central RSVP stream for targets, and thus will have adopted a much narrower central attentional focus than in the present study, where targets were presented unpredictably at one lateral position (in Experiment 1) or at the top or bottom position (in Experiments 2 and 3). A narrow central focus of attention is likely to reduce the probability of attentional capture by peripheral distractors. However, in their Experiments 4 and 5, Leblanc et al. (2008) also found no evidence for capture (i.e., no N2pc) by salient peripheral distractors in the same dimension (color) that did not match the exact feature value of the target under conditions where targets were presented simultaneously with two distractors on the vertical midline, and target detection should therefore have required a broader attentional focus.

Figure Captions

Figure 1. Example of search displays used in Experiments 1 to 3. In Experiment 1, color and shape target and nontarget singletons were presented at one of 10 lateral positions, but never at the top or bottom position (top panels). Dotted outlines represent red, dashed outlines represent blue, and solid outlines represent green. In reality, all shapes were filled in with the indicated color. In Experiments 2 and 3, targets were always presented at either the top or bottom position (middle panel). In Experiment 3, nontarget displays contained a shape nontarget singleton and a color nontarget singleton at diametrically opposite positions on the left or right side (bottom panel).

Figure 2. Grand averaged ERPs elicited to singleton stimuli in Experiment 1 at posterior electrodes PO7/PO8 contralateral (solid lines) and ipsilateral (dashed lines) to the position of the singleton. ERPs are shown separately for search arrays containing a color singleton (left) or a shape singleton (right), separately for targets (top panels), relevant-dimension nontargets (middle panels), and irrelevant-dimension nontargets (bottom panels). Insets show topographic maps of N2pc scalp distributions (seen from the back of the head) obtained during the 200–280 ms post-stimulus time interval for targets and relevant-dimension nontargets. These maps were constructed by spherical spline interpolation (see Perrin, Pernier, Bertrand, & Echallier, 1989) after mirroring the contralateral-ipsilateral difference waveforms to obtain symmetrical voltage values for both hemispheres. The N2pc appears as negative voltage (-) over the left hemisphere and as positive voltage (+) over the right hemisphere. Note that different voltage scales are used in target and nontarget maps.

Figure 3. Grand averaged ERPs elicited to nontarget singleton stimuli in Experiment 2 at posterior electrodes PO7/PO8 contralateral (solid lines) and ipsilateral (dashed lines) to the position of the singleton. ERPs are shown separately for search arrays containing a color singleton (left) or a shape singleton (right), separately for relevant-dimension nontargets (top panels), and irrelevant-dimension nontargets (bottom panels). Insets show topographic maps of N2pc scalp distributions (seen from the back of the head) obtained during the 200–280 ms post-stimulus time interval for relevant-dimension nontargets.

Figure 4. Grand averaged ERPs elicited at posterior electrodes PO7/PO8 in Experiment 3 on nontarget trials where color and shape nontarget singletons were presented

simultaneously at diametrically opposite positions on the left and right side, shown separately for the color task (left) and the shape task (right). Solid lines show ERPs elicited contralateral to the nontarget singleton defined in the currently task-relevant dimension, and dashed lines show ERPs contralateral to the singleton in the task-irrelevant dimension. Insets show topographic maps of N2pc scalp distributions (seen from the back of the head) obtained during the 200–280 ms post-stimulus time interval for both tasks.

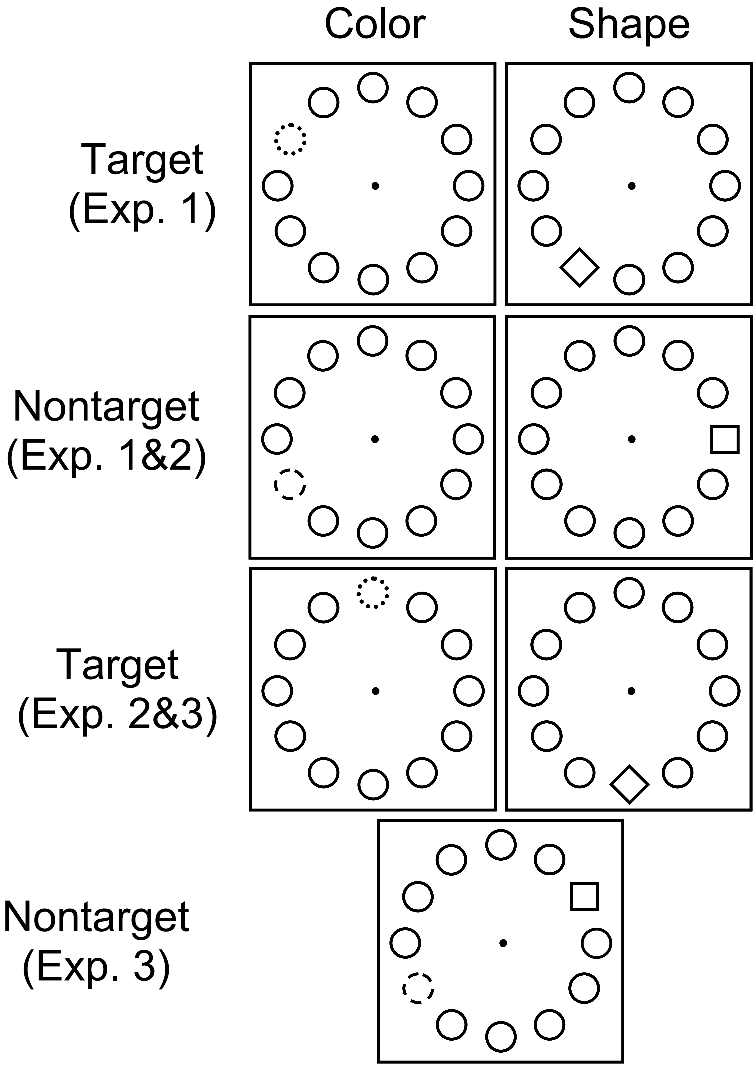
Color
Shape
Target
(Exp. 1)
Nontarget
(Exp. 1&2)
Target
(Exp. 2&3)
Nontarget
(Exp. 3)

Figure 1

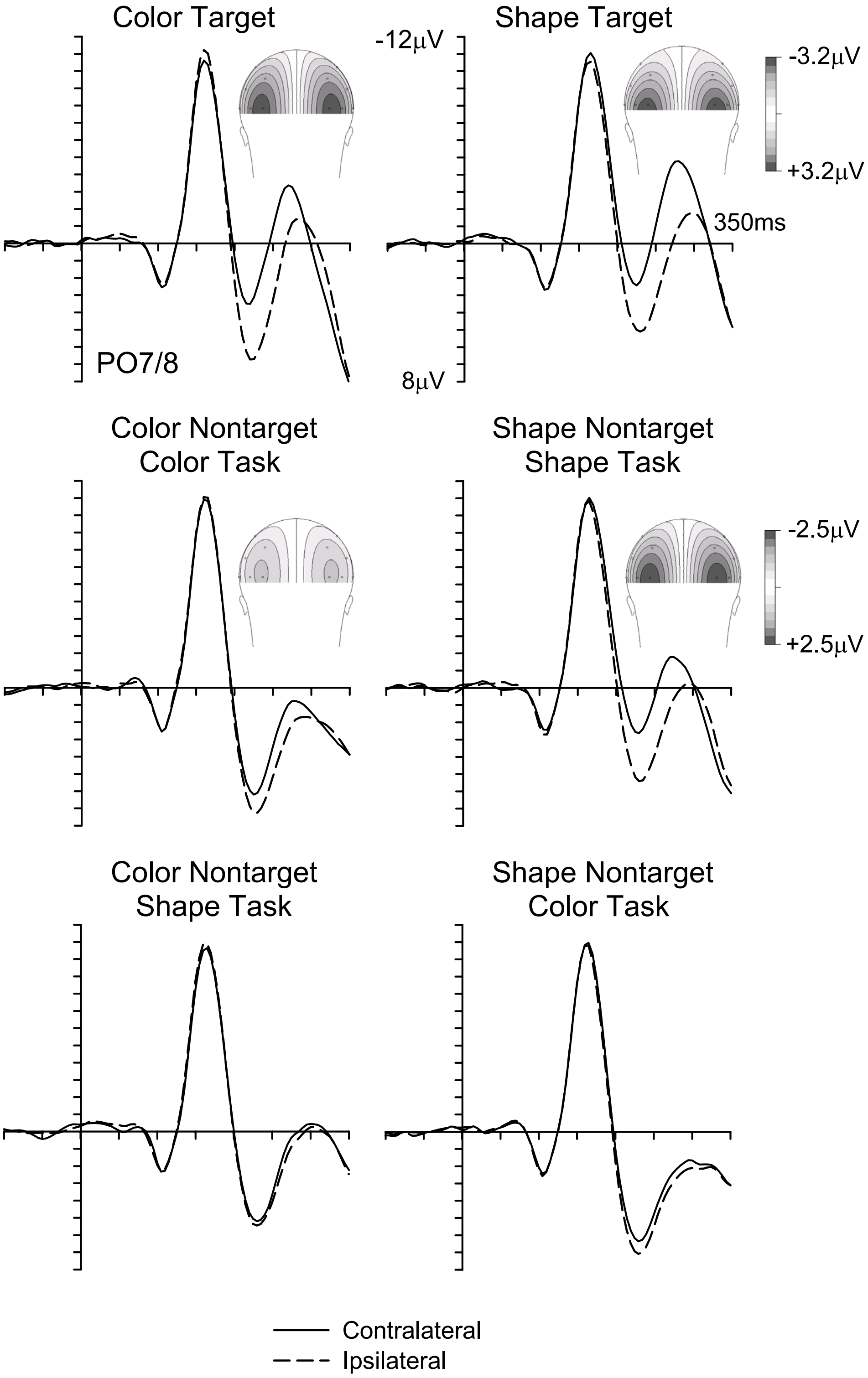
Color Target
Shape Target
-12μV
8μV
PO7/8
-3.2μV
+3.2μV
350ms
Color Nontarget
Color Task
Shape Nontarget
Shape Task
-2.5μV
+2.5μV
Color Nontarget
Shape Task
Shape Nontarget
Color Task
Contralateral
Ipsilateral

Figure 2

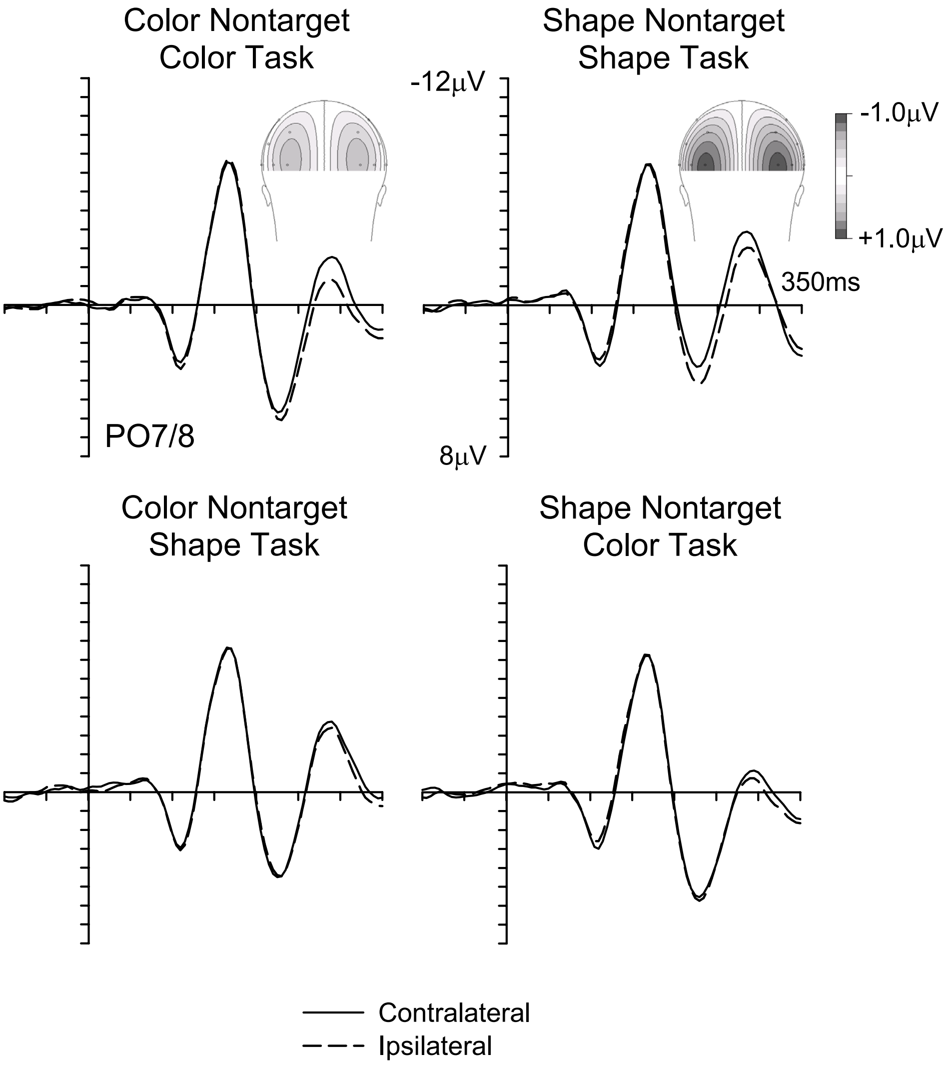
Color Nontarget
Color Task
Shape Nontarget
Shape Task
-12μV
8μV
-1.0μV
+1.0μV
350ms
PO7/8
Color Nontarget
Shape Task
Shape Nontarget
Color Task
Contralateral
Ipsilateral

Figure 3

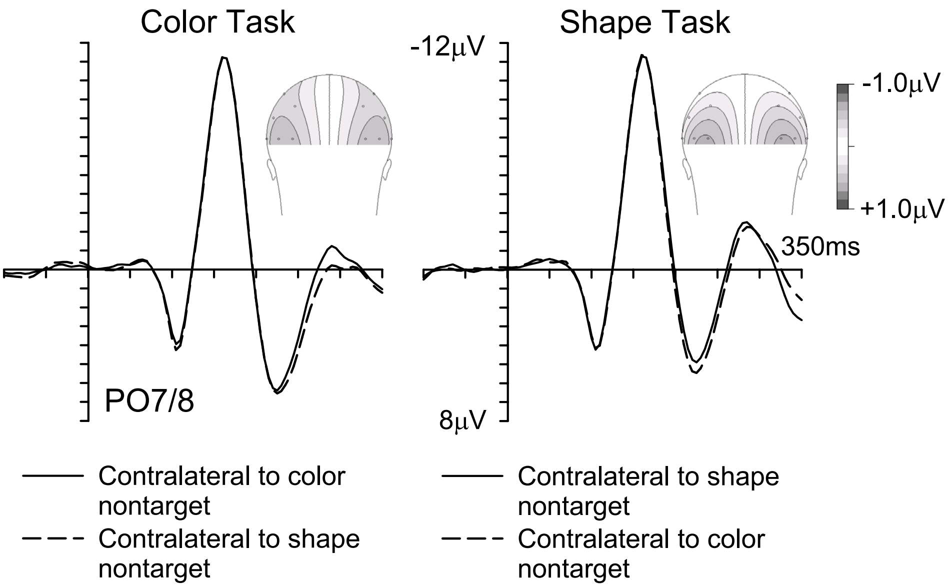
Color Task
Shape Task
-12μV
8μV
350ms
PO7/8
-1.0μV
+1.0μV
Contralateral to color nontarget
Contralateral to shape nontarget
Contralateral to shape nontarget
Contralateral to color nontarget

Figure 4