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Does focused endogenous attention prevent attentional capture in pop-out visual search?

ELLEN SEISS,[a] MONIKA KISS,[b] AND MARTIN EIMER[b]

[a]Department of Psychology, University of Surrey, Guildford, UK
[b]School of Psychology, Birkbeck College, University of London, UK

Abstract

To investigate whether salient visual singletons capture attention when they appear outside the current endogenous attentional focus, we measured the N2pc component as a marker of attentional capture in a visual search task where target or nontarget singletons were presented at locations previously cued as task-relevant, or in the uncued irrelevant hemifield. In two experiments, targets were either defined by color or by a combination of color and shape. The N2pc was elicited both for attended singletons and for singletons on the uncued side, demonstrating that focused endogenous attention cannot prevent attentional capture by salient unattended visual events. However, N2pc amplitudes were larger for attended and unattended singletons that shared features with the current target, suggesting that top-down task sets modulate the capacity of visual singletons to capture attention both within and outside the current attentional focus.

Descriptors: Attention, Spatial attention, Non-spatial attention, Visual search, Electrophysiology, Event-related brain potentials

Spatial attention can be directed in a voluntary (endogenous) way to specific locations, in order to selectively process stimuli that are relevant to current intentions. But attention can also be attracted in an involuntary (exogenous) fashion by salient external events, such as abrupt onsets or perceptually unique singleton stimuli, even when they are task-irrelevant. It therefore seems natural to assume a fundamental dichotomy between two types of attentional processes—endogenous attention that is goal-directed and determined by intentional task sets, and exogenous attention that is independent of top-down intention and triggered in a purely stimulus-driven fashion. However, the question whether a purely exogenous bottom-up mode of attentional capture actually exists has been the focus of considerable controversy. It has been claimed that the capture of attention by salient visual objects is always mediated in a top-down fashion by attentional control settings, which ensure that such objects will attract attention only if they possess currently task-relevant attributes (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). The alternative view is that attentional capture is determined solely by the low-level sensory properties of stimuli in the visual field, such that attention is captured by the most salient item in a bottom-up fashion, irrespective of current goals (e.g., Theeuwes, 1991b).

This debate about the role of top-down task sets in attentional capture has remained largely unresolved. However, there appears to be one instance where top-down control does indeed prevent attentional capture: Under conditions where spatial attention has already been endogenously allocated to a specific region in the visual field, the appearance of a salient but irrelevant visual event at another unattended location will not attract attention. This has been demonstrated in several behavioral studies (Yantis & Jonides, 1990; Theeuwes, 1991a) where visual search displays were preceded by informative spatial cues that indicated the location of the visual search target. Abrupt onset items that appeared at one of the uncued (unattended) positions did not delay reaction times (RTs) to targets, suggesting that, in spite of their salience, these items did not capture attention in a bottom-up fashion when it had already been endogenously focused elsewhere.

However, results from a more recent study (Theeuwes, Kramer, & Atchley, 2001) challenge the hypothesis that salient items located outside the current focus of top-down endogenous attention do not trigger bottom-up attentional capture. In this study, endogenous attentional shifts to the left or right side were induced by spatial cues which were presented prior to a visual search array that contained a target-color singleton (a red tilted line) on the cued side. On some trials, a singleton distractor (another red line) was simultaneously presented on the uncued side. In contrast to earlier observations for abrupt onset stimuli (Yantis & Jonides, 1990; Theeuwes, 1991a), these unattended distractor singletons substantially delayed RTs to target stimuli at

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Address reprint requests to: Martin Eimer, School of Psychology, Birkbeck College, University of London, Malet Street, London WC1E 7HX, UK. E-mail: m.eimer@bbk.ac.uk

cued locations, indicating that distractors were processed in spite of the fact that endogenous attention was focused elsewhere. Theeuwes et al. (2001) accounted for these distractor interference effects by assuming that both target and distractor singletons were processed in parallel during an early pre-attentive stage. They found that distractors produced smaller interference effects when attention had previously been cued to the opposite side than in a control condition without attentional cues, which led them to suggest that focused endogenous attention delays, but does not completely prevent, the processing of currently unattended visual stimuli. This interpretation is consistent with results from single unit recordings (Treue & Martinez Trujillo, 1999; McAdams & Maunsell, 2000) and fMRI studies (Saenz, Buracas, & Boynton, 2002), which have suggested that feature-based attention and spatial attention operate independently and in parallel: When attention was directed to a non-spatial feature (color or motion) in one visual hemifield, a stimulus that shared this attended feature in the opposite unattended hemifield triggered increased responses of feature-specific visual neurons. However, there is an alternative explanation for the distractor interference effects observed by Theeuwes et al. (2001). Rather than assuming that these effects were caused by the parallel processing of visual singletons within and outside the current focus of attention, one could instead argue that attention was frequently captured by color singleton distractors, in spite of the fact that these were always located outside the current focus of spatial attention. According to this interpretation, focused endogenous attention cannot always prevent attentional capture by salient stimuli at other task-irrelevant locations.

The aim of the present study was to use event-related brain potential (ERP) measures to gain new insights into whether focused endogenous attention can or cannot prevent attentional capture by salient visual events outside the current attentional focus. In addition, we also investigated whether and how the task-relevance of non-spatial visual features might affect attentional capture by visual singletons at attended and unattended locations. Arrow precues presented at the start of each trial instructed participants to direct their attention to the left or right side. These cues were followed by visual search displays that contained one singleton stimulus, either on the cued side or the uncued side (see Figure 1). In order to maximize the participants' incentive to direct their attention fully to the cued side, target-nontarget discriminations were only required for singletons that appeared on the cued side, while singletons on the uncued side could always be ignored. Participants had to respond to predefined target singletons on the cued side, while withholding a response to nontarget singletons on this side. Singletons on the uncued side were always response-irrelevant, irrespective of whether they had any target-defining features. In Experiment 1, targets were defined by their color (red singletons were targets and green singletons were nontargets, or vice versa). In Experiment 2, target singletons were defined by a combination of color and shape (e.g., green circles), and nontarget singletons shared one or neither of the target-defining features (e.g., green diamonds, blue circles, or blue diamonds).

Our central question was whether an endogenous focus of attention in one visual hemifield would completely prevent attentional capture by singleton stimuli that appeared in the opposite unattended hemifield. To obtain an electrophysiological marker of attentional capture, we measured the N2pc component in response to the visual search displays. The N2pc is an enhanced negativity over posterior scalp electrodes contralateral

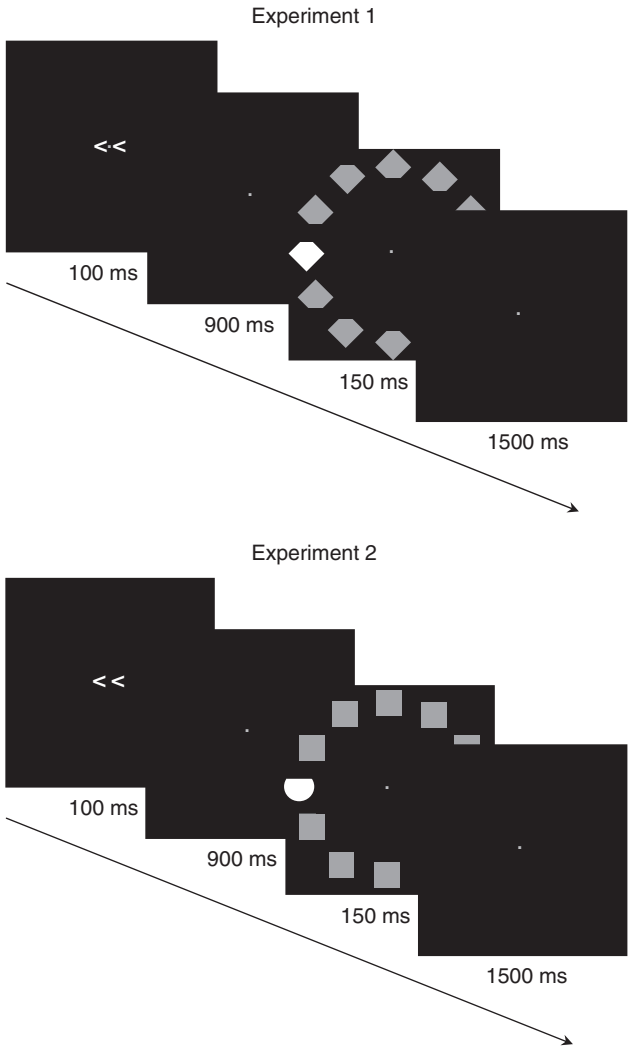

Figure 1. Trial structure in Experiment 1 (top) and Experiment 2 (bottom). In the trials shown here, central informative cues directing attention to the left side are followed by a singleton stimulus on the cued side. Participants had to respond to the cut side (top or bottom) of a target singleton on the cued side (or on either side, following uninformative cues in Experiment 1). Targets were defined by their color (red or green) in Experiment 1, and by a specific combination of color (blue or green) and shape (diamond or circle) in Experiment 2. Distractors were gray diamonds in Experiment 1, and gray squares in Experiment 2. Target colors (red, blue, or green) are shown as white in Figure 1.

to the side of an attended stimulus, originates primarily from ventral occipito-temporal cortex (Hopf et al., 2000), and is typically elicited between 180 ms and 300 ms after stimulus onset. Numerous previous studies have employed the N2pc component to investigate the deployment of selective attention in visual search tasks, and have established firm links between the presence of this component and the attentional selection of candidate target events among distractors (Eimer, 1996; Girelli & Luck, 1997; Kiss et al., 2007; Kiss, Van Velzen, & Eimer, 2008b; Luck & Hillyard, 1994a, 1994b; Mazza, Turatto, Umiltà, & Eimer, 2007; Woodman & Luck, 1999), as well as attentional capture by salient but task-irrelevant stimuli (e.g., Eimer & Kiss, 2008; Hickey, McDonald, & Theeuwes, 2006; Jolicœur, Sessa,

Dell'Acqua, & Robitaille, 2006; Kiss, Jolicœur, Dell'Acqua, & Eimer, 2008a).

Importantly, the N2pc is not triggered in response to any salient event in the visual field regardless of its task relevance, but is closely linked to the status of such events as potential targets for an attentional task. This has been demonstrated in a study by Luck and Hillyard (1994b), where target or nontarget singleton stimuli were presented among homogeneous distractors, and targets were defined by a specific combination of color, size, and orientation, while nontarget singleton items either shared two of these features with the targets ('difficult' nontargets) or differed from the targets on all three dimensions ('easy' nontargets). An N2pc was elicited in response to difficult nontargets, but not easy nontargets, as only the former required attentional processing in order to be distinguished from targets, whereas the latter could be rejected as task-irrelevant without any in-depth attentional analysis. Further evidence for a close link between the N2pc and selective attentional processing comes from our recent study (Eimer & Kiss, 2008) demonstrating that an N2pc to color singleton cues is only elicited when these cues match the known color of subsequent singleton targets, but not under conditions where targets are defined in a different dimension (onset or size). Finally, the N2pc does not reflect preparatory shifts of endogenous spatial attention to task-relevant locations, but is instead linked to the subsequent attentional selection of candidate target stimuli. This was demonstrated in a recent experiment (Kiss et al., 2008b) where the N2pc to target stimuli in a visual search array was unaffected by whether these stimuli were preceded by spatially informative or non-informative precues.

If an endogenous focus of attention in one hemifield prevents attentional capture by visually salient singletons in the opposite unattended hemifield (and any interference effects by such stimuli are due to parallel pre-attentive processing, as suggested by Theeuwes et al., 2001), an N2pc should be triggered exclusively on trials where singletons are presented on the cued side, but not for trials where singletons appear on the uncued side. In contrast, if salient singleton stimuli capture attention regardless of the current locus of spatial attention, an N2pc should be observed not only for singletons at attended locations, but also when singletons are presented on the opposite uncued side.

Even if ERP results were to show that focused endogenous spatial attention cannot completely prevent attentional capture by unattended visual singletons, this does not necessarily imply that such capture effects are entirely determined in a bottom-up fashion by stimulus salience, because they could still be contingent upon whether or not singleton stimuli possess target-defining non-spatial features. To investigate this possibility, we measured the N2pc for singletons with and without target features, separately for attended and unattended locations. For trials where these singletons appeared at cued (attended) locations, predictions were clear: The N2pc to nontarget singletons (e.g., green singletons when targets were red) should be attenuated relative to the N2pc to target singletons, indicative of a modulatory effect of top-down task set on attentional capture (see Kiss et al., 2008a, for similar results). The critical question was whether any N2pc to singletons on the uncued side would be similarly affected by task set. If singleton stimuli outside the current focus of attention trigger capture solely in virtue of their bottom-up salience, the N2pc to these stimuli should be unaffected by whether they possess target-defining features. Alternatively, if task set determines attentional capture by stimuli within as well as outside the current focus of attention, an N2pc might be observed for singletons on the uncued side that share features with the current target, but not for singletons without target-defining properties.

Experiment 1

In Experiment 1, each trial contained one red or green singleton stimulus that was always presented on the horizontal midline in the left or right visual field, and was accompanied by eleven gray distractor items in a circular visual search array (see Figure 1, top panel). On two-thirds of all trials, informative cues (left-pointing or right-pointing double arrows) presented at the start of each trial indicated the task-relevant side for this trial. Participants had to direct their attention to the cued side, in order to detect and respond to singletons in one target color (red or green) when these were presented on this side. They had to ignore nontarget-color singletons on the cued side, as well as all singletons on the uncued side, regardless of their color. On one-third of all trials, uninformative cues ('$<>$') were presented instead. In these trials, responses were required to target-color singletons on either side, and no preparatory attention shift to the left or right side was therefore required. All stimuli were diamonds with a cut at the top or bottom (Figure 1, top panel), and responses to target singletons were determined by the location of this cut (top or bottom).

The N2pc component was measured in response to visual search arrays that contained a target-color or a nontarget-color singleton, separately for trials where this singleton appeared on the cued side or on the uncued side, and for trials with uninformative cues. In addition, we also measured ERPs in the interval between informative cues and subsequent visual search displays, in order to demonstrate that attention was indeed directed to the cued side in response to informative cues. Previous studies of visual-spatial orienting (c.f., Eimer, Van Velzen, & Driver, 2002; Harter, Miller, Price, LaLonde, & Keyes, 1989; Praamstra, Boutsen, & Humphreys, 2005) have shown that attention shifts are accompanied by distinct lateralized ERP components in the cue-target interval. An anterior directing attention negativity (ADAN) started about 350 ms after cue onset at frontocentral electrodes, and was followed by a late directing attention positivity (LDAP) at posterior electrodes. These lateralized ERP components are commonly assumed to reflect successive phases in the control of spatial attention, such as the initiation of a lateral attention shift and the preparatory activation of visual brain areas (see Harter et al., 1989; Eimer et al., 2002; Praamstra et al., 2005). The presence of these two components would provide evidence that participants directed their attention to the left or right side in response to informative cues, as instructed, thereby confirming that singletons on the cued or uncued side of subsequent visual search displays were indeed located within or outside the current focus of spatial attention. In addition to the ADAN and LDAP, another lateralized component has frequently been observed between 250 and 400 ms after cue onset at posterior electrodes (e.g., Harter et al., 1989). While this early directing attention negativity (EDAN) has often been linked to attention shifts, more recent evidence (Van Velzen & Eimer, 2003) suggests that it may primarily reflect a lateralized visual response triggered by asymmetric visual cues, such as left- or right-pointing arrows. It should also be noted that the status of the ADAN as a marker of attentional control is not uncontroversial. For example, Green, Conder, and McDonald (2008)

have recently provided evidence for two distinct neural generators that contribute to the ADAN, and have argued that neither of these is directly linked to shifts of attention (see also Green, Teder-Sälejärvi, & McDonald, 2005).

Materials and Methods

Participants. Eighteen paid volunteers participated in the experiment. Five were excluded due to poor eye gaze control in the cue-target interval (see below), and one other was excluded due to a low signal-to-noise ratio. Thus twelve participants (9 females), aged 18–37 years (mean age: 25.1 years), remained in the sample. All participants were right handed and had normal or corrected to normal vision.

Stimuli, Apparatus, and Procedure. Participants were tested in a dimly lit room, and fixated a dot displayed continuously on the center of a computer monitor located at a viewing distance of 57 cm. Response keys were located 21 cm (top key) and 16.5 cm (bottom key) in front of the participant, aligned with the body midline. On each trial, a central left-pointing, right-pointing, or symmetrical double arrow cue ('<<', '>>', '<>'; size: 1.5° × 0.75°) was displayed for 100 ms and followed after an empty interval of 900 ms by a visual search array (150 ms duration). The interval between the offset of a search array, and the onset of the cue on the next trial was 1500 ms. Search arrays consisted of 12 equiluminant (5.7 cd/m^2) diamonds arranged in a circle around the screen center (circle diameter: 9.6°, diamond size: 1.5° × 1.5°). All diamonds had a cut randomly determined at the top or bottom. Eleven diamonds were gray, one was either red or green, and this color singleton was always presented at the 3 or 9 o'clock position (Figure 1, top panel).

Following informative cues ('<<' or '>>'), participants had to direct their attention to the left or right side (while maintaining central fixation), as indicated by these cues. They had to respond to the cut side (top or bottom) of singletons in the predefined target color (red or green, counterbalanced across participants) when these were presented on the cued side by pressing the spatially corresponding response key. Singletons in the nontarget color and all singletons on the uncued side had to be ignored. Following uninformative cues ('<>'), participants had to maintain a diffuse attentional focus, to respond to singletons in the target color on either side, and to ignore all nontarget-color singletons.

Twenty experimental blocks with 72 trials per block were run. Informative and uninformative cues were presented on 48 and 24 trials, respectively. Following informative cues, target-color and nontarget-color singletons were presented equiprobably on the cued side (valid trials) or uncued side (invalid trials). Thus, response-relevant targets were presented on 24 trials per block (12 informative cue trials with target-color singletons on the cued side, and 12 uninformative cue trials with targets on either side). The assignment of response hand (left or right) to response key (top or bottom) was changed after ten blocks, and the order of this assignment was counterbalanced across participants.

EEG Recording and Data Analysis. EEG was DC-recorded from 25 Ag-AgCl electrodes relative to a left earlobe reference (all impedances below 5kΩ; 250 Hz sampling rate; 40 Hz upper cut-off frequency), and was digitally re-referenced to the average of the left and right earlobe. EEG epochs were computed separately in response to the precue (−100 to 1000 ms relative to cue onset), and to the visual search array (−100 ms to 500 ms relative to array onset), relative to a 100 ms pre-stimulus baseline. Trials with eyeblinks (Fpz exceeding ±80 μV), horizontal eye movements (HEOG exceeding ±30 μV), or other artefacts (a voltage exceeding ±80 μV at any electrode) were excluded. Averaged horizontal electro-oculogram (HEOG) waveforms to informative cues were scored for systematic deviations of eye position, indicating residual eye movements towards the cued location. HEOG deviations exceeding ±3.5 μV led to the disqualification of five participants.

Lateralized ERP components obtained in the interval between informative cues and subsequent search arrays were computed at electrodes ipsi- and contralateral to the side of a cued attentional shift. The ADAN was quantified on the basis of mean amplitude values obtained at lateral anterior sites (F3/4, FC5/6, F7/8) during the 350–500 ms interval after cue onset. The LDAP was measured during the 550–750 ms post-cue interval at lateral posterior sites (P3/4, P7/8, PO7/8), and the EDAN was quantified for the 250–400 ms post-cue time window at the same sites. Mean amplitudes were analyzed by repeated measures ANOVAs for the factors electrode site and lateralization (electrode ipsilateral vs. contralateral to the cued side). Effect sizes for ADAN, LDAP, and EDAN components were calculated as partial eta-squared (η_p^2), to determine the proportion of the effect plus error variance attributable to the effect.

The EEG in response to visual search arrays was averaged for all combinations of singleton color (target vs. nontarget-color), singleton location (left vs. right), and cue type (valid vs. invalid vs. uninformative cue). N2pc amplitudes were quantified on the basis of ERP mean amplitudes obtained between 180 and 240 ms after search array onset at lateral posterior electrodes PO7/8 ipsi- and contralateral to the color singleton. Repeated measures ANOVAs were conducted for the factors singleton color, lateralization (electrode ipsilateral vs. contralateral to the side where the singleton was presented), and cue type. N2pc latency measures were based on difference waveforms computed by subtracting ERPs recorded ipsilateral to the singleton location from contralateral ERPs, for different cue types and singleton colors. N2pc onset latencies were determined using a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998), and were defined as the point in time when the N2pc reached a criterion amplitude of −0.8 μV.[1] They were analyzed in a repeated measures ANOVA with the factors singleton color and cue type, with *t*-values and *F*-values adjusted according to the formulas recommended by Miller et al. (1998) and Ulrich and Miller (2001).

For all ANOVAs, within-subject effects were corrected for non-sphericity using the Huynh-Feldt correction. Significant effects were further analyzed using post-hoc *t*-tests for paired samples where the critical α-level was Bonferroni corrected.

[1] An absolute amplitude criterion was used for onset latency measures because N2pc peak amplitudes varied substantially across conditions. When using an alternative relative onset criterion (such as 50% peak amplitude), onset latencies of large-amplitude components are likely to be overestimated relative to components with smaller peak amplitudes. However, with an absolute criterion, larger-amplitude components may reach the criterion amplitude earlier, resulting in a relative underestimation of the real onset latency. Because of this general difficulty in accurately estimating N2pc onset latencies between conditions where N2pc peak amplitudes vary considerably, all latency estimates reported in this article need to be interpreted with caution.

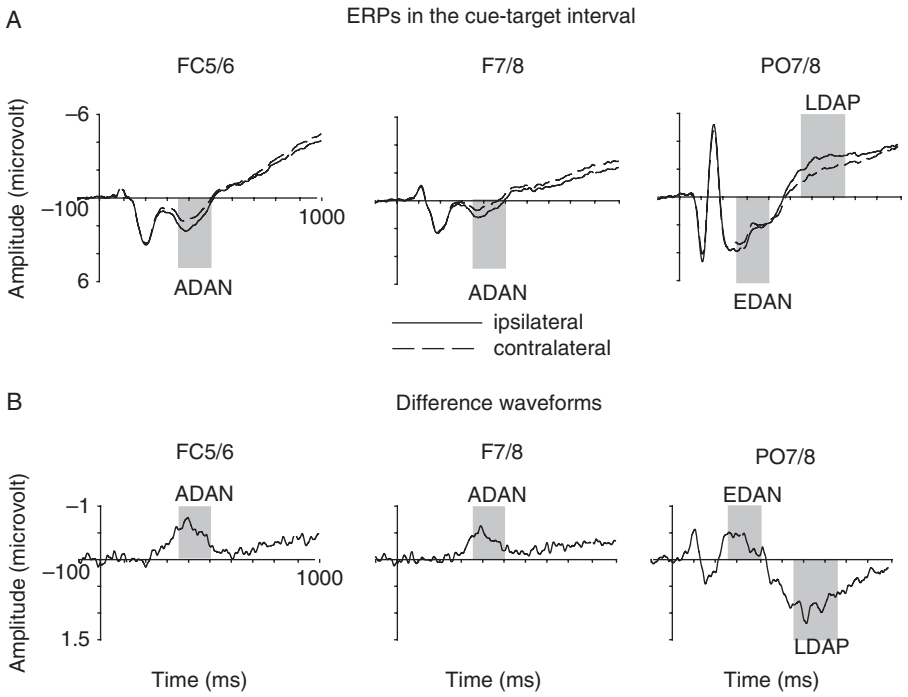

Figure 2. (A) Grand-averaged ERPs elicited in Experiment 1 in response to informative cues in the 1000 ms interval following cue onset at lateral anterior electrodes FC5/6 and F7/8 and lateral posterior electrodes PO7/8 ipsilateral and contralateral to the cued side. ADAN: anterior directing attention negativity; EDAN: early directing attention negativity; LDAP: late directing attention positivity. (B) Difference waveforms obtained by subtracting ERPs elicited ipsilateral to the cued side from contralateral ERPs in the 1000 ms interval following informative cue onset.

Results

Behavioral Performance. Correct responses to target-color singletons were faster when these targets were preceded by valid cues than by uninformative cues (586 ms vs. 615 ms; $t[11] = 3.5$, $p < .01$). Incorrect responses (choice errors) to targets occurred on 1.4% and 1.6% of all valid and uninformative cue trials. Participants missed 0.3% and 1.9% of all response-relevant targets in valid and uninformative cue trials. The false alarm rate for target-color singletons on the uncued side was 6.8%, and responses to nontarget-color singletons occurred on 0.02% of all trials.

Lateralized ERP Components During Covert Attentional Shifts. Figure 2 shows ERPs to informative cues at lateral anterior electrodes (FC5/6, F7/8) and lateral posterior electrodes PO7/8 ipsilateral and contralateral to the cued attentional shift, together with difference waveforms calculated by subtracting ipsi- from contralateral ERPs. Both lateralized components previously observed during cued attention shifts (ADAN and LDAP) were present. This was confirmed by main effects of lateralization at lateral anterior electrodes in the 350–500 ms post-cue interval ($F[1,11] = 21.6$, $\eta_p^2 = .66$, $p < .01$), and at lateral posterior electrodes in the 550–750 ms interval ($F[1,11] = 15.4$, $\eta_p^2 = .58$, $p < .01$). The presence of ADAN and LDAP components demonstrates that endogenous attentional shifts were indeed triggered by informative cues.[2] In addition, an earlier contralateral negativity was elicited at lateral posterior electrode sites, resulting in a main effect of lateralization during the 250–400 ms post-cue interval ($F[1,11] = 9.7$, $\eta_p^2 = .47$, $p < .01$). This reflects the presence of the EDAN component (see Figure 2) that was triggered in response to the asymmetric arrow stimuli used as informative cues here.

Lateralized Posterior ERP Components to Visual Search Arrays. Figure 3 shows ERPs in response to the visual search array at lateral posterior electrodes PO7/8 ipsi- and contralateral to the side where the color singleton was presented. ERPs are shown separately for trials with valid, invalid, and uninformative cues, and for target-color and nontarget-color singletons. An N2pc was clearly present for target-color singletons (Figure 3, top row), as well as for nontarget-color singletons (Figure 3, bottom row), although its amplitude was reduced. Importantly, very similar N2pc components were elicited for color singletons at attended locations (valid cue), unattended locations (invalid cue), and for uninformative cue trials. This is further illustrated in Figure 4A, which shows difference waveforms obtained by subtracting ipsilateral from contralateral ERPs at PO7/8 for all three cue types and both singleton colors.

[2]An alternative way to investigate whether participants used informative spatial precues to direct their attention in preparation for upcoming targets is to directly compare ERPs elicited in response to informative and uninformative spatial precues (see Talsma, Slagter, Nieuwenhuis, Hage, & Kok, 2005). In Experiment 1, ERPs to informative cues (collapsed across left and right cues) were characterized by an enhanced positivity between 250 and 400 ms after cue onset at posterior electrodes (P7, P8, PO7, PO8: $F[1,11] = 24.3$, $p < .001$) relative to uninformative cues. This was followed by a broadly distributed enhanced negativity between 400 and 600 ms that was maximal over centroparietal sites (C3, Cz, C4, P3, Pz, P4: $F[1,11] = 16.1$, $p < .002$). This pattern of an early positivity followed by a central negativity is similar to the results previously observed by Talsma et al. (2005), who interpreted these observations as evidence for the endogenous orienting and subsequent maintenance of focal attention, and thus provides additional evidence for the claim that informative cues did elicit shifts of spatial attention.

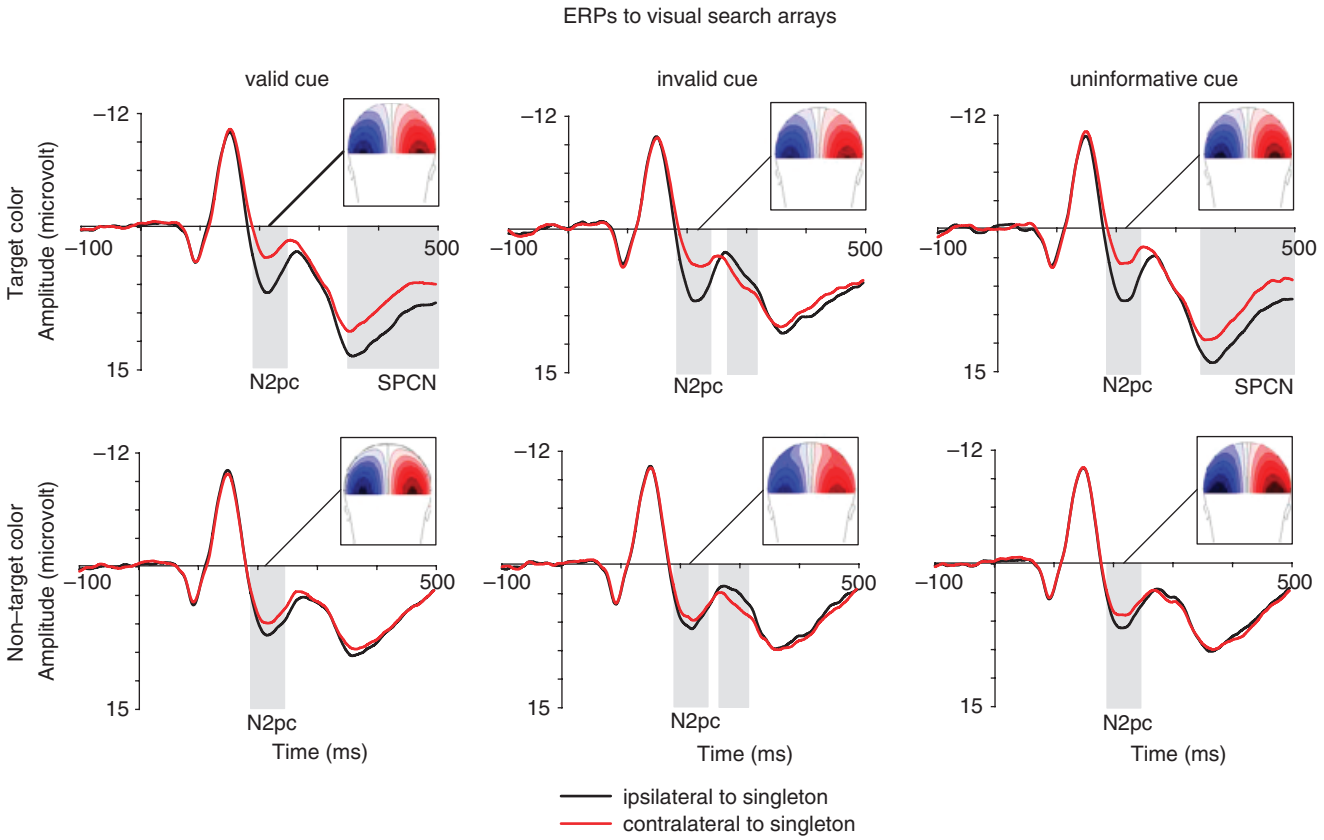

Figure 3. Grand-averaged ERPs elicited in Experiment 1 in the 500 ms interval following the onset of the visual search display at lateral posterior electrodes PO7/8 ipsilateral (black lines) and contralateral (red lines) to the side of a color singleton, shown separately for valid trials, invalid trials, and trials with uninformative cues. Topographical maps represent differences between brain activity over hemispheres ipsi- and contralateral to the color singleton in a 24 ms time window centered around the N2pc peak amplitudes in the grand average waveforms. They were constructed by spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989) after mirroring the difference amplitudes to obtain symmetrical but inverse amplitude values for both hemispheres. For target-color singletons (top row), amplitudes range between -3.75 and 3.75 μV (contour lines represent changes of 0.5 μV). For nontarget-color singletons (bottom row), amplitudes range between -0.9 and 0.9 μV (contour lines represent changes of 0.12 μV).

A main effect of lateralization ($F[1,11] = 34.1$, $p < .01$) on ERP mean amplitudes in the N2pc time window (180–240 ms after array onset) confirmed the presence of the N2pc. N2pc amplitudes were strongly modulated by singleton color ($F[1,11] = 33.8$, $p < .01$), indicative of a strong effect of top-down color task set on the spatially selective processing of color singletons. A larger N2pc was triggered by target-color singletons (-3.2 ± 0.5 μV) relative to nontarget-color singletons (-0.8 ± 0.2 μV). However, the N2pc was reliably present not only for target-color singletons ($t[11] = 6.0$, $p < .01$), but also for nontarget-color singletons ($t[11] = 4.4$, $p < .01$).

Most importantly, there was no interaction between lateralization and cue type ($F < 1$). This demonstrates that an N2pc was triggered in response to color singletons regardless of whether attention was unfocused, focused at the location where this singleton appeared, or focused in the opposite hemifield (see Figure 4A). In addition, there was no interaction between cue type, target color, and lateralization ($F < 1$), indicating that the modulation of N2pc amplitudes by the currently active color task set was also unaffected by the current focus of attention. To confirm the presence of an N2pc, and its top-down modulation by color task set, in invalid trials where attention was focused in the opposite hemifield, an additional analysis was conducted for these trials only. A main effect of lateralization ($F[1,11] = 41.7$, $p < .01$) demonstrated that the N2pc was elicited by color singletons at unattended locations, and an interaction between lateralization and target color ($F[1,11] = 26.3$, $p < .01$) showed that N2pc amplitudes were strongly affected by color attention. Follow-up analyses revealed that a reliable N2pc was triggered on invalid trials for target-color singletons ($t[11] = 5.5$, $p < .01$), and also, albeit in an attenuated fashion, for nontarget-color singletons ($t[11] = 4.1$, $p < .01$).

The current color task set also affected N2pc latencies, as N2pc onset was delayed for nontarget-color singletons. This is illustrated in Figure 4B, which shows contralateral minus ipsilateral difference waves for trials with target-color and nontarget-color singletons, collapsed across all three cue types. A jackknife-based analysis (Miller et al., 1998) revealed a delayed N2pc onset for nontarget-color singletons (199 ms) compared to target-color singletons (163 ms; $F[1,11]_{\text{corrected}} = 13.2$, $p < .01$). This latency shift was not modulated by cue type ($F < 1$). In an analysis conducted for invalid trials only, an analogous N2pc onset difference was obtained for nontarget-color and target-color singletons (200 ms vs. 164 ms; $t[11]_{\text{corrected}} = 19.2$, $p < .01$), thereby confirming a reliable effect of top-down color task set on N2pc latency when attention was focused in the opposite hemifield.

A later sustained posterior contralateral negativity (labelled 'SPCN' in Figures 3 and 4A) was observed at PO7/8 between 350

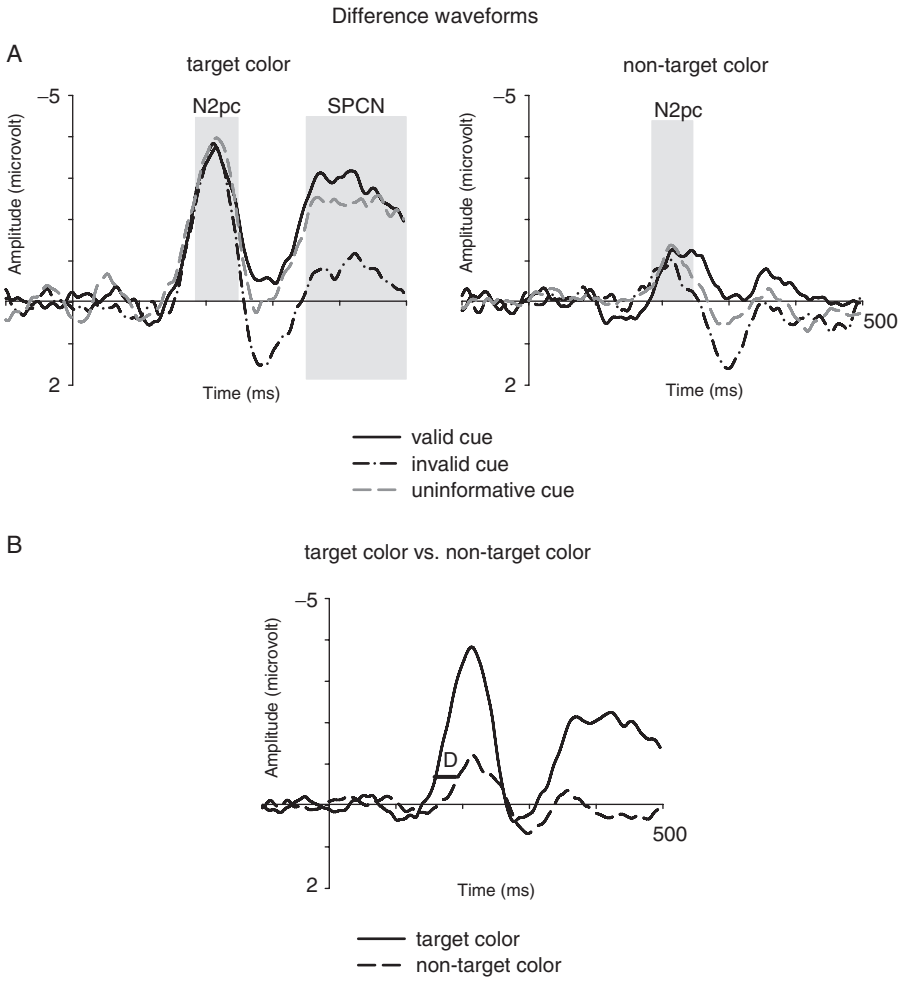

Figure 4. (A) Difference waveforms obtained in Experiment 1 at lateral posterior electrodes PO7/8 in the 500 ms interval following search array onset, obtained by subtracting ERPs elicited ipsilateral to the side of a color singleton from contralateral ERPs. Waveforms are shown separately for target-color and nontarget-color singletons, for trials with valid cues (solid black lines), uninformative cues (dashed gray lines), and invalid cues (dashed black lines). (B) Contralateral-ipsilateral difference waveforms at PO7/8 in the 500 ms interval following search array onset for target-color (solid line) and nontarget-color singletons (dashed line), collapsed across all three cue types, showing modulations of N2pc amplitude and onset latency by color task set.

and 500 ms after search array onset, but only for trials where response-relevant targets were presented (i.e., trials where valid or uninformative cues preceded target-color singletons). This was confirmed by a three-way interaction between lateralization, cue type, and singleton color ($F[2,22] = 12.2$, $p < .01$) in an analysis of ERP mean amplitudes in the 350–500 ms post-stimulus time window. Further analyses demonstrated the presence of a contralaterally enhanced negativity for target-color singletons preceded by valid ($t[11] = 4.5$, $p < .001$) or uninformative cues ($t[11] = 4.3$, $p < .01$), but not for any of the other four combinations of cue type and singleton color (all $t[11] < 2.0$).

Finally, and unexpectedly, a lateralized effect of opposite polarity was triggered at PO7/8 in the time interval between the N2pc and the SPCN, but only for search arrays that were preceded by invalid cues (indicated by shaded areas in Figure 3). An interaction between lateralization and cue type ($F[2,22] = 15.1$, $p < .01$) was found for ERP mean amplitudes obtained between 270 and 320 ms post-stimulus. The enhanced negativity ipsilateral to the color singleton location was reliable for invalid trials ($F[1,11] = 21.5$, $p < .001$), but absent for trials with uninformative or valid cues (both Fs < 1).

Discussion of Experiment 1

The results of Experiment 1 suggest that endogenous attention cannot prevent attentional capture by salient visual events at task-irrelevant locations. An N2pc was triggered in response to color singleton stimuli not only when these stimuli were presented within the current attentional focus (i.e., on the side indicated by informative cues), or when attention was unfocused (i.e., on trials with uninformative cues), but also, critically, on trials where these singletons were presented in the uncued and thus unattended visual hemifield. Moreover, the amplitudes and onset latencies of these N2pc components were essentially unaffected by the current locus of spatial attention (see Figure 4A). As the N2pc is an established electrophysiological marker of selective attentional processing and attentional capture (e.g., Eimer, 1996; Eimer & Kiss, 2008; Hickey et al., 2006; Luck & Hillyard, 1994a, 1994b), this pattern of results indicates that the

current locus of endogenous spatial attention has little if any impact on the capacity of color singletons to capture attention.

The absence of any effects of cued spatial attention on the N2pc would be less surprising if informative cues had for some reason failed to trigger shifts of attention towards the cued side. However, lateralized ERP components indicative of covert attentional orienting (ADAN, LDAP) were reliably elicited during the cue-target interval in response to informative cues, and RTs to targets were faster on valid trials than on trials with uninformative precues, where attention was unfocused. These findings strongly suggest that, as instructed, participants directed their attention to the side specified by informative cues, and that singletons presented on the uncued side were located well outside the current focus of attention.

However, the observation that an N2pc was elicited in response to unattended color singletons does not necessarily imply that these singletons had captured attention in an entirely bottom-up fashion. In fact, the results of Experiment 1 suggest that attentional capture was strongly modulated by the task-relevance of the singletons' color. The N2pc was reduced in amplitude and appeared to emerge later (but see footnote 1) on trials where nontarget-color singletons were presented, relative to trials with target-color singletons (see Figures 3 and 4). This suggests that the attentional selection of singleton items was delayed and less efficient for items that did not match the top-down color task set (see also Kiss et al., 2008a, for similar results). Importantly, this pattern of results was observed regardless of whether singletons were presented at attended locations, followed spatially uninformative cues, or appeared on the uncued unattended side. The fact that the N2pc in response to singletons outside the current attentional focus was modulated by whether or not these singletons matched the target color strongly suggests that attentional capture by unattended stimuli is not driven exclusively by their bottom-up salience, but is instead mediated by top-down task set.

In addition to the N2pc, a later lateralized posterior negativity was elicited in Experiment 1 between 350 and 500 ms after search array onset, but only on trials that contained response-relevant target singletons (i.e., target-color singletons presented at cued locations or on trials with uninformative cues; see Figures 3 and 4A). This component is almost certainly equivalent to the sustained posterior contralateral negativity (SPCN) that has previously been observed in tasks where lateralized target stimuli had to be maintained in visual working memory for further analysis (e.g., Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur et al., 2006; McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004). An SPCN has also been observed in a visual search task where the shape of briefly presented singleton stimuli needed to be discriminated (Mazza et al., 2007). In the present study, such discrimination was required to locate the cut in response-relevant targets, but not in nontarget-color singletons or singletons on the uncued side. Accordingly, the SPCN was elicited only for the former type of stimuli.

Finally, another lateralized effect was observed at posterior electrodes on trials where target-color or nontarget-color singletons were presented on the uncued side. On these trials, an 'inverted N2pc' (i.e., an enhanced negativity ipsilateral to the side of the color singleton) followed the initial N2pc component (see Figures 3 and 4A). Because this finding was not predicted, it needs to be interpreted with caution. Given its polarity, it is possible that this lateralized effect reflects a shift of attention away from a singleton on the task-irrelevant side towards the opposite visual hemifield, and possibly also the attentional selection of a distractor stimulus at the cued location (see also Woodman & Luck, 1999, for a polarity reversal of the N2pc that was interpreted as reflecting attention shifts between visual hemifields). Such rapid 'corrective' attentional shifts might be elicited in a reflexive fashion when a salient visual stimulus has attracted attention away from its current focus. Alternatively, they could also reflect an endogenous shift of attention back to the cued task-relevant side. One aim of Experiment 2 was to confirm that such an inverted N2pc is reliably elicited whenever singleton stimuli appear in the uncued and thus unattended hemifield.

Experiment 2

The results of Experiment 1 suggest that, when observers are set to detect a specific color singleton target at a known location, color singletons presented in the opposite unattended hemifield will capture attention. One could argue that this may have been due to the fact that target detection was relatively easy, as target and nontarget singletons could be distinguished on the basis of a simple perceptual feature (color). Under conditions where target detection is more demanding, attention might be more tightly focused at cued task-relevant locations, and therefore less likely to be captured by singletons located outside this attentional focus. The aim of Experiment 2 was to investigate this possibility. In contrast to Experiment 1, targets were now defined by a combination of color and shape. On each trial, one of four singleton stimuli (a green diamond, a blue diamond, a green circle, or a blue circle) was presented with equal probability against a background of gray square distractors (see Figure 1, bottom panel). One of these singletons served as target, while the other three were nontargets, and target identity varied across participants. As in Experiment 1, informative precues specified the task-relevant side, and responses were only required to target singletons presented at this cued side. Nontarget singletons on the cued side and all singleton stimuli on the uncued side had to be ignored. Trials with uninformative cues were not included in Experiment 2.

Because targets were now defined by a specific combination of color and shape, nontarget singletons could match the target color, but not its shape (C+S−), match the target shape, but not its color (C−S+), or possess neither of the two target-defining features (C−S−). The N2pc component was measured in response to target singletons and these three different types of nontarget singletons separately for trials where they were presented on the cued or uncued side. As in Experiment 1, the presence of an N2pc component to singletons on the uncued side would be indicative of attentional capture by stimuli outside the current attentional focus. One central question was whether this component would now be delayed or attenuated relative to the N2pc observed for singletons on the cued side, or perhaps even be entirely absent. Another question was whether attentional capture would again be modulated by top-down task set, as reflected by systematic N2pc differences between targets and the three different types of nontarget singletons, and whether such top-down effects on attentional capture would be found both within as well as outside the current focus of endogenous attention.

Materials and Methods

Participants. Sixteen paid volunteers participated in the experiment. Three were excluded due to poor eye gaze control in

the cue-target interval (see below), and one other was excluded due to a low signal-to-noise ratio. Thus twelve participants (4 females), aged 24–33 years (mean age: 27 years), remained in the sample. All participants were right-handed and had normal or corrected to normal vision.

Stimuli, Apparatus, and Procedure. These were identical to Experiment 1, with the following exceptions. Circular search arrays now consisted of 11 gray distractor squares and one singleton item. This singleton was a blue or green diamond or circle with a cut randomly on the top or bottom. All stimuli were equiluminant (2.1 cd/m^2). Stimulus colors and luminance were changed relative to Experiment 1 in order to ensure that the relative discriminability of color and shape singletons was as equal as possible (see below). Only informative cues ('<<' or '>>') were presented, and participants had to direct their attention to the left or right side (while maintaining central fixation), as indicated by these cues, and to respond to the cut side (top or bottom) of a singleton on the cued side when it matched both target-defining attributes (color and shape). As in Experiment 1, singletons were always presented at the 3 or 9 o'clock positions (see Figure 1, bottom panel). Singletons in the target-color and nontarget shape (C+S−), in the target shape and nontarget-color (C−S+), and singletons in the nontarget-color and shape (C−S−) were to be ignored, as were all singletons on the uncued side, regardless of their color and shape. Target-defining color (blue or green) and shape (circle or diamond) were counterbalanced across participants.

Sixteen experimental blocks with 64 trials per block were run. Each singleton type (C+S+, C+S−, C−S+, C−S−) was presented randomly and equiprobably on the cued side (valid trials) or uncued side (invalid trials). Thus, C+S+ singletons were presented on 16 trials per block. Eight of those appeared on the cued side and thus required a response, and eight were presented on the uncued side. C+S−, C−S+, and C−S− singletons were each also presented on 16 trials per block (eight on the cued side, and eight on the uncued side). The assignment of response hand (left or right) to response key (top or bottom) was changed after eight blocks, and the order of this assignment was counterbalanced across participants.

To confirm that there were no systematic salience and discriminability differences between the color and shape singletons used here, eight of the twelve participants also performed a control task at the end of the experiment. This task consisted of four blocks with 64 trials each. No cues were presented, but search arrays were identical to the main experiment. Participants had to respond to the top/bottom cut of one target singleton type defined by a specific color (regardless of its shape), or a specific shape (regardless of its color), while ignoring singletons in the other color or shape. All four singleton features (blue, green, circle, diamond) served as targets in one block, with order of blocks counterbalanced across participants. Mean RTs to blue, green, circle, and diamond singletons were 519 ± 80 ms, 506 ± 69 ms, 512 ± 63 ms, and 531 ± 88 ms. There was no significant effect of singleton type ($F[3,21] = 1.65$, $p = .21$), thereby suggesting that the color and shape singleton features used in Experiment 2 did not differ systematically in terms of their discriminability. The frequency of choice errors and false alarms was also not significantly different across singleton types.

EEG Recording and Data Analysis. EEG recording, data processing, and artefact rejection were identical to Experiment 1. HEOG deviations exceeding ± 3.5 μV led to the disqualification of three participants. EDAN, ADAN, and LDAP components were quantified and analyzed as in Experiment 1. The EEG in response to visual search arrays was averaged for all combinations of singleton color (C+ vs. C−), singleton shape (S+ vs. S−), singleton location (left vs. right), and cue type (valid vs. invalid). The N2pc was quantified on the basis of ERP mean amplitudes obtained at lateral posterior electrodes PO7/8 ipsi- and contralateral to the singleton in the 200 and 260 ms interval after search array onset. This N2pc analysis window was shifted by 20 ms relative to Experiment 1, because the N2pc emerged slightly later in Experiment 2. This N2pc delay is due to a general reduction in the salience of all singletons. In order to ensure that color and shape singletons were approximately equal in terms of their discriminability (see above), the relative salience of color singletons among gray distractors was reduced relative to Experiment 1, as was overall stimulus luminance. Repeated measures ANOVAs were conducted with the variables singleton color, singleton shape, lateralization (electrode ipsilateral vs. contralateral to the side of the singleton), and cue type. N2pc latency analyses were analogous to Experiment 1.

Results

Behavioral Performance. Mean RTs for target singletons (C+S+) presented at the cued side were 629 ± 116 ms. Incorrect responses (choice errors) to cued target singletons were present in 1.8% of the trials. Participants missed 1.3% of all cued targets. The false alarm rate for invalidly cued target singletons was 1.6%, and responses to nontarget singletons occurred on less than 0.1% of all trials.

Lateralized ERP Components During Covert Attentional Shifts. Figure 5 shows ERPs at lateral anterior electrodes (FC5/6, F7/8) and lateral posterior electrodes PO7/8 ipsilateral and contralateral to the cued attentional shift, together with difference waveforms calculated by subtracting ipsi- from contralateral ERPs. A main effect of lateralization at lateral anterior electrodes in the 350–500 ms post-cue interval ($F[1,11] = 146.8$, $\eta_p^2 = .93$, $p < .01$) confirmed the presence of the ADAN. The amplitude of the ADAN varied between anterior electrode pairs ($F[2,22] = 3.5$, $\eta_p^2 = .24$, $p < .05$), but was significant for each of these pairs (all $t[11] > 10.1$, all $p < .01$). At lateral posterior electrodes, the lateralization effect only approached significance ($F[1,11] = 4.0$, $\eta_p^2 = .27$, $p = .07$) in the 550–750 ms post-cue interval, but was accompanied by a lateralization × electrode site interaction ($F[2,22] = 4.2$, $\eta_p^2 = .28$, $p < .03$). Follow-up analyses revealed a significant lateralization effect at electrode pair PO7/8 ($t[11] = 2.6$, $p < .025$), reflecting the presence of the LDAP component. No reliable LDAP was found at P3/4 ($t[11] = 1.2$, p = n.s.) and P7/8 ($t[11] = 1.6$, p = n.s.). As in Experiment 1, an early directing attention negativity (EDAN) was elicited at lateral posterior electrode sites, resulting in a main effect of lateralization during the 250–400 ms post-cue interval ($F[1,11] = 26.4$, $\eta_p^2 = .71$, $p < .01$).

Lateralized Posterior ERP Components to Visual Search Arrays. Figure 6 shows ERPs in response to visual search arrays at lateral posterior electrodes PO7/8 ipsi- and contralateral to the side where the singleton was presented. An N2pc was clearly present when the singleton was displayed in the target color and shape (top left). The N2pc was also elicited in response to nontarget singletons, although its amplitude was reduced. It was

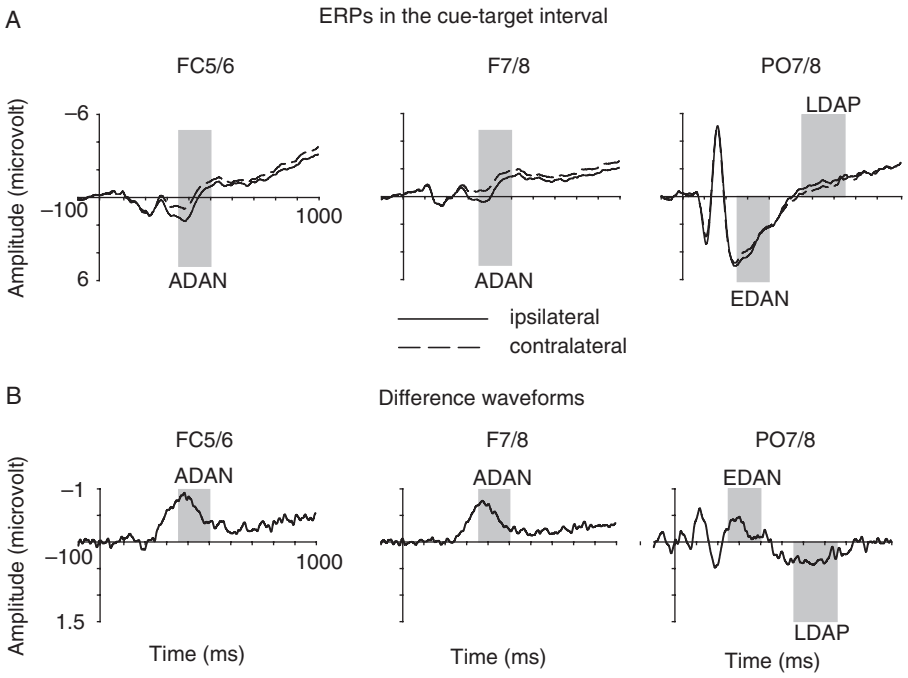

Figure 5. (A) Grand-averaged ERPs elicited in Experiment 2 in response to informative cues in the 1000 ms interval following cue onset at lateral anterior electrodes FC5/6 and F7/8 and lateral posterior electrodes PO7/8 ipsilateral and contralateral to the cued side. ADAN: anterior directing attention negativity; EDAN: early directing attention negativity; LDAP: late directing attention positivity. (B) Difference waveforms obtained by subtracting ERPs elicited ipsilateral to the cued side from contralateral ERPs in the 1000 ms interval following informative cue onset.

smallest for C − S − singletons that matched neither the target color nor its shape. These modulatory effects of top-down task set on the N2pc were present for singletons at cued (attended) as well as at uncued (unattended) locations. This is further illustrated in Figure 7, which displays difference waveforms computed by subtracting ipsi- from contralateral waveforms, for each of the four singleton types, separately for valid and invalid trials (top and middle panels). C+ and C − singletons are represented by black and gray lines, while S+ and S − singletons are shown as solid and dashed lines. A direct comparison between the N2pc in valid and invalid trials is provided in Figure 7 (bottom panel). In contrast to the results observed in Experiment 1, the N2pc to singletons at uncued locations was attenuated and delayed relative to the N2pc triggered by singletons at cued locations.

To simplify presentation, we first describe the general effects of singleton type (C+S+, C+S−, C−S+, C−S−) on the N2pc irrespective of the locus of attention, before considering the effects of cue type (valid vs. invalid). A main effect of lateralization ($F[1,11] = 35.8$, $p < .01$) on ERP mean amplitudes in the N2pc time window (200–260 ms after array onset) confirmed the presence of the N2pc. N2pc amplitudes were modulated by singleton color ($F[1,11] = 44.8$, $p < .01$). The interaction between lateralization and singleton shape was almost significant ($F[1,11] = 4.5$, $p = .06$). The largest N2pc was triggered by C+S+ singletons (-3.4 ± 1.9 μV, $t[11] = 6.1$, $p < .001$). Although smaller, reliable N2pc components were also elicited by C+S− (-2.8 ± 1.5 μV, $t[11] = 6.5$, $p < .001$), C−S+ (-1.7 ± 1.2 μV, $t[11] = 4.7$, $p < .001$), and C−S− singletons (-1.3 ± 1.2 μV, $t[11] = 3.8$, $p < .003$). In addition, the task relevance of singleton features also affected N2pc latencies. As in Experiment 1, N2pc onset was delayed for singletons in the nontarget-color relative to target-color singletons (212 vs. 190 ms; see also Figure 7, gray vs. black lines), and this was substantiated by a main effect of singleton color on N2pc onset latency ($F[1,11]_{corrected} = 10.1$, $p < .01$). In contrast, N2pc onset latencies for S+ and S − singletons (199 vs. 203 ms) did not differ significantly ($F[1,11]_{corrected} = 1$).

In contrast to Experiment 1, the N2pc was now attenuated and delayed for unattended singletons relative to singletons on the cued side (see Figure 7, bottom panel). An interaction between lateralization and cue type was observed for N2pc amplitudes ($F[1,11] = 7.3$, $p < .02$), confirming larger N2pc components on valid trials (-2.9 ± 1.7 μV, $t[11] = 5.8$, $p < .001$) than on invalid trials (1.7 ± 1.3 μV, $t[11] = 4.6$, $p < .001$). N2pc onset latencies were 192 ms for valid trials and 210 ms for invalid trials, and this difference resulted in a nearly significant main effect of cue type ($F[1,11]_{corrected} = 4.6$, $p = .054$). However, and importantly, modulatory effects of top-down task set on N2pc amplitudes and latencies were similarly present on valid trials where singletons were attended (Figure 7, top panel) and on invalid trials where they were presented outside the current attentional focus (Figure 7, middle panel). Accordingly, and in line with the results of Experiment 1, there were no significant higher-order interactions between lateralization, cue type, singleton color, and singleton shape (all Fs$[1,11] < 1.3$). To confirm that the N2pc was reliably modulated by task set when singletons were presented in the unattended hemifield, additional mean amplitude and latency analyses were conducted for invalid trials only. A main effect of lateralization for ERP mean amplitudes in the N2pc time window ($F[1,11] = 21.7$, $p < .01$) demonstrated that the N2pc was reliably elicited by singletons at unattended locations. An interaction between lateralization and singleton color ($F[1,11] = 43.1$, $p < .01$) confirmed that N2pc amplitudes were

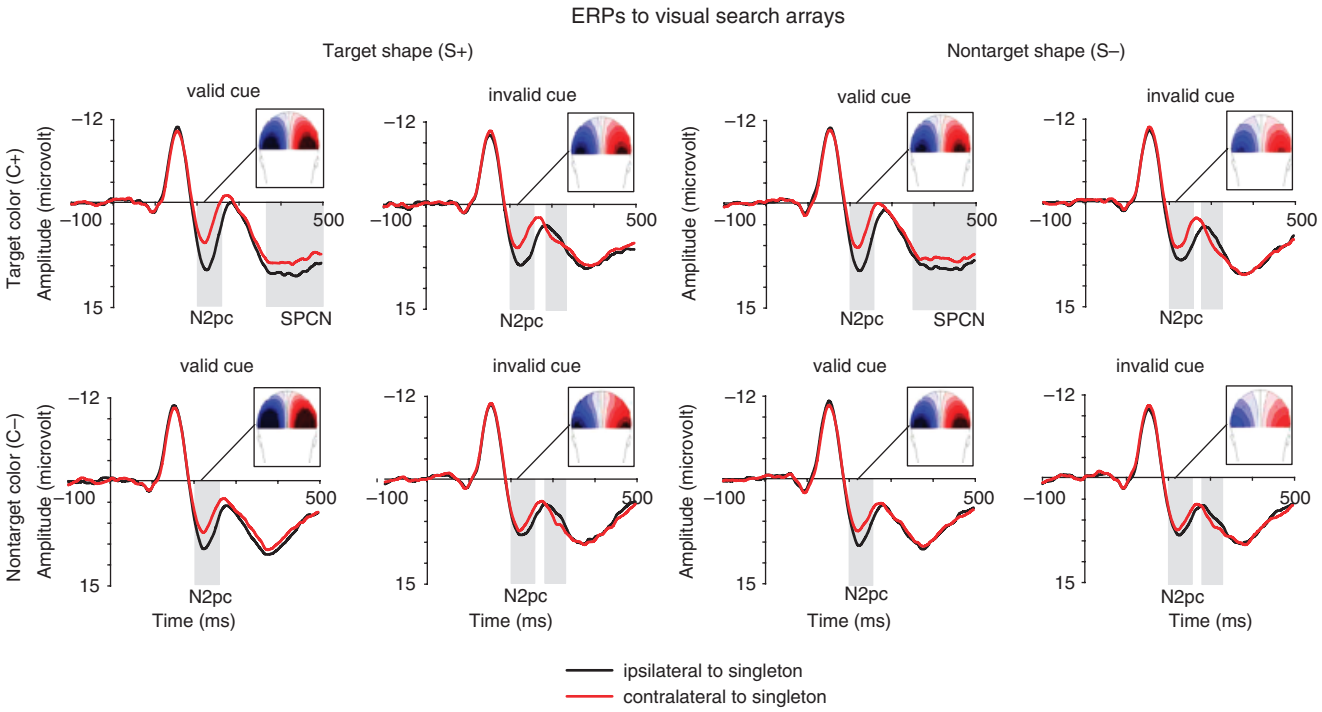

Figure 6. Grand-averaged ERPs elicited in Experiment 2 in the 500 ms interval following the onset of the visual search display at lateral posterior electrodes PO7/8 ipsilateral (black lines) and contralateral (red lines) to the side of the singleton. Waveforms are shown separately for each combination of cue type (valid vs. invalid), singleton color (target vs. nontarget-color), and singleton shape (target vs. nontarget shape). Topographical maps represent differences between brain activity over hemispheres ipsi- and contralateral to the singleton in a 24 ms time window centered around the N2pc peak amplitudes in the grand average waveforms, constructed by spherical spline interpolation after mirroring the difference amplitudes to obtain symmetrical but inverse amplitude values for both hemispheres. For target-color singletons (top row), amplitudes range between -3.75 and 3.75 μV (contour lines represent changes of 0.5 μV). For nontarget-color singletons (bottom row), amplitudes range between -1.8 and 1.8 μV (contour lines represent changes of 0.24 μV).

modulated by whether or not an unattended singleton possessed the target-defining color. Although the N2pc was also numerically larger for S+ as compared to S− singletons on the uncued side (see Figure 7, middle panel), the interaction between lateralization and singleton shape was not significant ($F[1,11] = 2.8$, $p = .12$). Follow-up analyses revealed that a reliable N2pc to uncued singletons was present for C+S+ stimuli ($t[11] = 6.1$, $p < .001$), C+S− stimuli ($t[11] = 5.5$, $p < .001$), and for C−S+ stimuli ($t[11] = 2.5$, $p < .03$). For C−S− stimuli, the N2pc was nearly significant ($t[11] = 2.1$, $p = .06$). Finally, color task set also had a significant effect on N2pc onset latencies in response to stimuli on the uncued side (188 ms vs. 230 ms for C+ and C− singletons, respectively, $t[11]_{corrected} = 2.8$, $p < .02$). There was no N2pc onset latency difference between uncued S+ and S− singletons (210 ms vs. 209 ms).

As in Experiment 1, a sustained posterior contralateral negativity (SPCN) was observed at PO7/8 between 350 and 500 ms after search array onset, most prominently for response-relevant target singletons at the cued location (see Figures 6 and 7). This was reflected by interactions between lateralization and singleton color ($F[1,11] = 14.8$, $p < .01$), lateralization and singleton shape ($F[1,11] = 4.8$, $p < .05$), between lateralization, singleton shape and cue type ($F[1,11] = 9.3$, $p < .01$), and an almost significant four-way interaction (Lateralization × Singleton color × Singleton shape × Cue type: $F[1,11] = 4.5$, $p = .06$). Follow-up analyses conducted separately for valid and invalid trials, and each singleton type, confirmed that no SPCN was triggered on invalid trials ($F < 1$). On valid trials, reliable SPCN was not only present for C+S+ singletons ($t[11] = 3.3$, $p < .007$), as expected, but also for C+S− singletons ($t[11] = 3.4$, $p < .005$). No reliable SPCN was elicited for valid trials with C−S+ or C−S− singletons (all $t < 1$).

Finally, and analogous to Experiment 1, an ipsilateral negativity ('inverted N2pc') was triggered at PO7/8 in the time interval between the N2pc and the SPCN, but only for singleton stimuli presented on the uncued side (see Figures 6 and 7). A significant interaction between lateralization and cue type ($F[1,11] = 5.9$, $p < .03$) was found for ERP mean amplitudes obtained in a 280 and 330 ms post-stimulus measurement window. Follow-up analyses, conducted separately for valid and invalid trials, confirmed that this 'inverted N2pc' was reliably present on invalid trials (-0.9 ± 1.3 μV, $F[1,11] = 5.7$, $p < .04$), but not on valid trials ($F < 1$).

Discussion of Experiment 2

The results of Experiment 2 confirmed and extended the findings of Experiment 1. As before, lateralized ERP components (ADAN and LDAP) were triggered in response to informative cues, demonstrating that participants did indeed direct their attention towards the cued side, as instructed. It should be noted that ADAN and LDAP components showed some differences between the two experiments. ADAN amplitudes varied across anterior electrodes in Experiment 2, and the LDAP was smaller than in Experiment 1. The fact that targets were defined by a more complex color-shape combination in Experiment 2 is likely to have increased the demands on non-spatial visual working

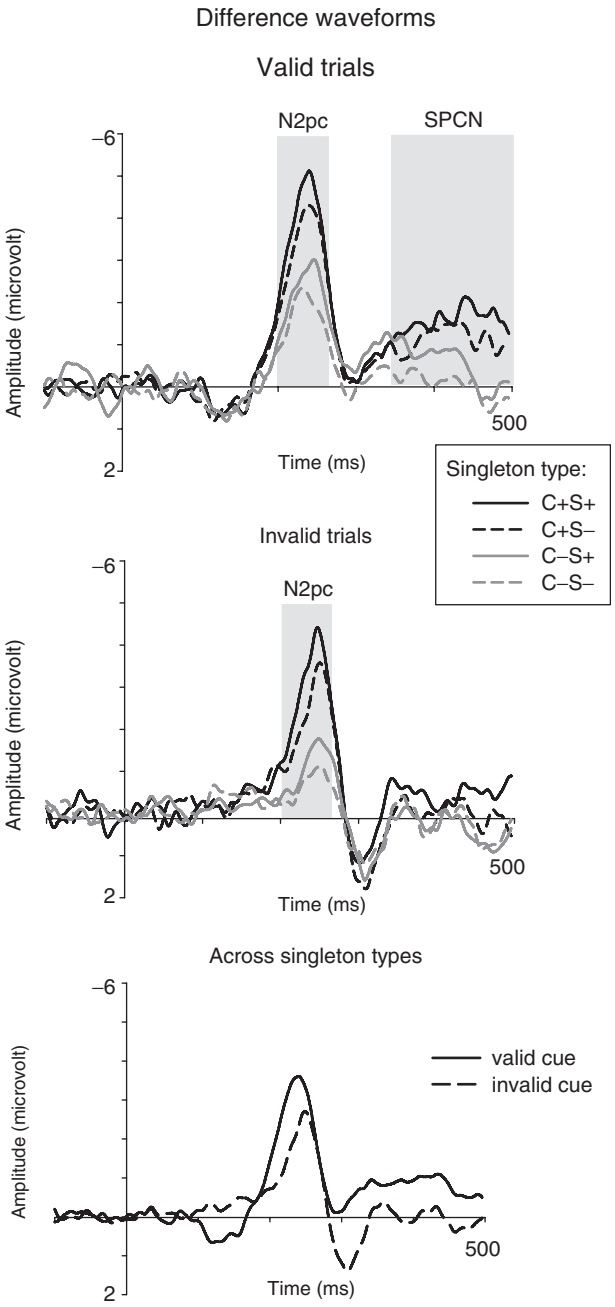

Figure 7. Difference waveforms obtained at lateral posterior electrodes PO7/8 in the 500 ms interval following search array onset, obtained by subtracting ERPs elicited ipsilateral to the side of singleton from contralateral ERPs. Waveforms are shown for each singleton type, separately for valid trials (top panel) and invalid trials (middle panel). The bottom panel shows difference waveforms for singletons at cued locations (valid trials, solid line) and uncued locations (invalid trials, dashed lines), each collapsed across all four singleton types.

memory during the cue-target interval, which may have reduced the amplitudes of lateralized ERP components associated with spatial orienting.

As in Experiment 1, singletons presented on the cued side within the current focus of endogenous attention triggered an N2pc, and this component was again modulated by top-down task set (see Figures 6 and 7): Its amplitude was maximal for target singletons, intermediate for singletons that shared one of the two target-defining attributes (C+S− and C−S+), and smallest for singletons that had neither of these attributes (C−S−). Most importantly, the N2pc was reliably present also for singletons that appeared on the task-irrelevant uncued side, thereby again demonstrating attentional capture outside the current attentional focus. Similar to the N2pc triggered by attended singletons, the N2pc to singletons on the unattended side was modulated by top-down task set (see Figures 6 and 7). This pattern of results is perfectly consistent with the findings of Experiment 1, and thus provides further evidence that attentional capture by singletons outside the current attentional focus is not an automatic result of their bottom-up salience, but is instead modulated by top-down task set.

As in Experiment 1, top-down task set for color also appeared to affect N2pc latencies, with estimated N2pc onsets later for C− as compared to C+ singletons (but see footnote 1), indicating that attentional capture was delayed when singleton stimuli did not match the currently relevant target color. This effect was reliably present also for singletons presented in the uncued visual hemifield. In contrast, no comparable N2pc latency effects were found for target as compared to nontarget shapes (S+ vs. S− singletons), suggesting that task sets for color and shape might differ systematically in their impact on the time course of attentional capture. This possibility needs to be investigated in future experiments.

The N2pc results discussed so far have confirmed the findings of Experiment 1 under conditions where the discrimination of target and nontarget singletons was more difficult, because targets were now defined by a combination of color and shape. However, there was one notable difference between experiments. In Experiment 1, N2pc amplitudes and latencies were virtually identical for singletons presented on the cued versus uncued side, suggesting that the current focus of endogenous spatial attention had little if any impact on attentional capture. In contrast, cued endogenous attention affected N2pc amplitudes and latencies in Experiment 2. N2pc amplitudes were reliably attenuated on invalid trials, and there was an almost significant onset latency difference, with N2pc onsets delayed by about 20 ms for singletons on the uncued side (see Figure 7, bottom panel). Relative to Experiment 1, attentional target selection was more difficult, and singleton stimuli were somewhat less salient in Experiment 2 (see above). Attention might therefore have been more tightly focused at cued task-relevant locations in Experiment 2, resulting in slightly faster and more efficient attentional capture by attended singletons as compared to singleton stimuli appearing in the opposite unattended visual hemifield. It is possible that the small differences in ADAN and LDAP components between experiments that was noted above may also be linked to differences in attentional allocation strategies.

In addition to these N2pc results, Experiment 2 also confirmed two further observations of Experiment 1. The SPCN component that is assumed to be linked to activity in visual short-term memory was again found to follow the N2pc to response-relevant C+S+ singletons on the cued side (see Figure 7). These stimuli required further in-depth analysis to determine the response-relevant location of their cut. As expected, no SPCN was present for cued C−S− singletons, or for any singleton in the uncued task-irrelevant hemifield, as these stimuli could be rapidly rejected as nontargets and thus be excluded from further processing. Interestingly, an SPCN was not just observed for cued C+S+ singletons, but was also reliably elicited

for C+S− singletons on the cued side, suggesting that some in-depth analysis of singletons at potentially task-relevant locations took place when these matched the target-defining color. In contrast, no reliable SPCN was obtained for cued C−S+ singletons. This difference suggests that singletons could be more rapidly excluded from further attentional processing when their nontarget status was indicated by their color than by their shape. The fact that singleton color (C+ vs. C−) had a more pronounced effect on N2pc amplitudes than singleton shape (S+ vs. S−) is also in line with this hypothesis.

Finally, Experiment 2 confirmed the presence of an 'inverted N2pc' (an enhanced negativity ipsilateral to the side where a singleton was presented) that followed the initial N2pc component on invalid trials only (see Figure 7). The fact that this lateralized effect was observed in both experiments strongly suggests that it is systematically related to the appearance of an irrelevant visual singleton outside the current focus of endogenous attention. As suggested before, this inverted N2pc might reflect a rapid attentional shift towards the side previously cued as task-relevant that is triggered after attention has been captured by a salient visual event on the task-irrelevant side.

General Discussion

The current ERP study has shown that a focus of endogenous attention in one visual hemifield does not prevent attentional capture by salient singleton stimuli that appear in the opposite unattended hemifield. We measured the N2pc component as an established electrophysiological marker of attentional capture in response to target and nontarget singletons which appeared either at a location that was previously cued as potentially task-relevant, or in the uncued irrelevant hemifield. Regardless of whether targets were defined simply by their color (in Experiment 1), or by a combination of color and shape (in Experiment 2), an N2pc was elicited not only in response to attended singletons on the cued side, but also for singletons that appeared outside the focus of attention on the uncued side. In Experiment 1, N2pc amplitudes and latencies were entirely unaffected by the current locus of endogenous attention. In Experiment 2, where the target-nontarget discrimination was more demanding, and the perceptual salience of singletons was reduced, a moderate effect of spatial cueing on the N2pc was obtained, as this component was attenuated and delayed for singleton stimuli on the uncued side. This difference suggests that the capacity of irrelevant unattended visual singletons to capture attention can be modulated to some degree by the perceptual demands of a focal attention task and/or by stimulus salience. Most importantly, however, was the observation that the N2pc remained reliably present for singletons at unattended locations in both experiments, demonstrating that salient visual events retain their capacity to capture attention even when endogenous attention is already focused elsewhere.

Our conclusion that focal endogenous attention does not prevent attentional capture by salient visual events presented in the unattended hemifield does, of course, critically depend on the assumption that the spatial precues employed in our study were indeed effective in initiating attention shifts towards the left or right side. While the presence of lateralized ERP components previously observed during cued shifts of spatial attention (ADAN, LDAP) provides electrophysiological evidence that participants did shift their attention as indicated by informative spatial cues, it might be argued that additional direct behavioral evidence is required to confirm this assumption. We therefore ran an additional behavioral control experiment, where stimuli and procedure were identical to Experiment 2, except that cues now predicted the side where a singleton stimulus was presented with 80% validity. Responses were required to all target stimuli (defined by a specific combination of color and shape, as in Experiment 2), regardless of whether they were presented on the cued or uncued side, while all other singleton stimuli (C+S−, C−S+, and C−S−) had to be ignored. Eight participants (6 females, mean age: 31 years) completed six experimental blocks with 80 trials per block. As expected, reaction times were substantially faster on trials where a C+S+ stimulus was presented at the cued location than on trials where this stimulus was presented on the opposite uncued side (580 ms vs. 660 ms). This difference resulted in a significant effect of spatial cueing ($t[7] = 5.6$, $p < .001$), thereby providing additional behavioral support for the critical assumption that the cues used in the present study were indeed effective in eliciting endogenous shifts of spatial attention.

The conclusion that focused endogenous attention cannot prevent attentional capture by color and shape singletons in the unattended hemifield is not in line with observations from behavioral studies (Yantis & Jonides, 1990; Theeuwes, 1991a) that found no interference effects of abrupt visual onsets at unattended locations on responses to attended targets. In these experiments, abrupt peripheral onsets were presented concurrently with targets, whereas color singletons were always presented in isolation in the present study. It is possible that the ability of unattended task-irrelevant singletons to capture attention is reduced or even completely eliminated when an additional target stimulus is simultaneously present. However, the results from a more recent behavioral study (Theeuwes et al., 2001) suggest that this may not be the whole story. Here, endogenous attention was cued to one side, but color singleton distractors on the unattended side still delayed RTs to simultaneously presented singleton targets on the opposite attended side. This demonstrates that focused endogenous attention does not prevent the processing of salient distractors at irrelevant locations, even when targets are simultaneously present. Theeuwes et al. (2001, Exp. 2) also found that distractor interference effects were larger when targets and distractors were mapped to different responses than when they were mapped to the same response, demonstrating that distractor identity was processed prior to response execution. Although these authors interpreted their findings as evidence for parallel pre-attentive processing of target and distractor information, they are equally compatible with the hypothesis that attention was captured by the distractor singleton on a substantial number of trials. Such an interpretation would be consistent with the results of the present study, and would imply that focused endogenous attention might be less effective in preventing attentional capture by color and shape singletons than in preventing capture by abrupt onsets (Yantis & Jonides, 1990; Theeuwes, 1991a).

The presence of an N2pc to visual singletons delivered outside the attentional focus may be taken to imply that these singletons capture attention in a purely bottom-up and stimulus-driven fashion. However, top-down task sets did still play an important role in modulating attentional capture. In both experiments, the N2pc to singleton stimuli was strongly affected by whether these singletons shared features with the target (see also Kiss et al., 2008a, for similar results). The N2pc was delayed and attenuated for singletons that did not match the currently active color task

set, and tended to be attenuated when they did not match the currently relevant target shape (in Experiment 2). Importantly, top-down effects of task set on the N2pc were observed not only for singletons at cued attended location, but were equally present in response to singletons that appeared on the unattended side. This observation is consistent with previous evidence from single unit and fMRI studies (McAdams & Maunsell, 2000; Saenz et al., 2002; Treue & Martinez Trujillo, 1999) demonstrating that spatial and feature-based attention can operate in parallel. The current ERP results suggest that task sets which specify currently relevant non-spatial attributes such as specific colors or shapes strongly affect the capacity of visual singletons to capture attention, regardless of whether they appear at currently attended or unattended locations. However, the fact that a significant, albeit attenuated, N2pc was also observed for singletons that did not have any task-relevant features (such as the C − S − singletons in Experiment 2) suggests that top-down task set does not completely determine attentional capture, but the bottom-up salience of singletons also plays a role (see also Kiss et al., 2008a, for further evidence for such task-set independent effects of salience on attentional capture). It is also interesting to note that the presence of an N2pc to C − S − singletons in Experiment 2 is not entirely consistent with the observation of Luck and Hillyard (1994b) that no N2pc was elicited by 'easy' nontargets, which differed from targets in three dimensions (orientation as well as color and size). Further research is needed to define the boundary conditions for salience-driven attentional capture that is independent of top-down task sets more comprehensively.

In summary, the present ERP study has obtained new insights into the interplay between endogenous and exogenous attention, and in particular into the role of focused endogenous attention for attentional capture. Focused endogenous spatial attention does not prevent attentional capture by salient but irrelevant visual singletons in the opposite unattended hemifield. However, this attentional capture is not a purely exogenous phenomenon, but is instead modulated in a top-down fashion by current task sets.

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