Attentional repulsion effects produced by feature-guided shifts of attention

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Attention shifts to particular objects in the visual field can distort perceptual location judgments. Visual stimuli are perceived to be shifted away from the current focus of attention (the attentional repulsion effect [ARE]). Although links between repulsion effects and stimulus-driven exogenous attentional capture have been demonstrated conclusively, it remains disputed whether AREs can also be elicited as a result of feature-guided attention shifts that are controlled by endogenous task sets. Here we demonstrate that this is indeed the case. Color singleton cues that appeared together with equiluminant gray items triggered repulsion effects only if they matched a current task-relevant color but not when their color was irrelevant. When target-color and nontarget-color singleton cues appeared in the same display, AREs emerged relative to the position of the target-color cue. By obtaining independent behavioral measures of perceptual repulsion and electrophysiological measures of attentional capture by target-color cues, we also showed that these two phenomena are correlated. Individuals who were more susceptible to attentional capture also produced larger AREs. These results confirm the existence of links between task-set contingent attentional capture and AREs. They also provide the first direct demonstration of the attentional nature of these effects with online brain activity measures: perceptual repulsion arises as the result of prior feature-guided attention shifts to specific locations in the visual field.

Introduction

Visual selective attention is responsible for the prioritization of objects and events to facilitate the adaptive control of cognition and action. Such attentional prioritization can be triggered in a stimulus-driven exogenous manner (e.g., by abrupt onsets or physically salient stimuli) or in an endogenous voluntary fashion. Both exogenous and endogenous attention result in performance benefits for visual objects at attended as compared with unattended locations (e.g., Henderson, 1991; Jonides, 1980; Posner, 1980; Posner & Cohen, 1984). In contrast to exogenous attention, voluntary attention is guided by currently active top-down task sets. Spatial task sets have been studied in experiments in which a spatial cue (e.g., a left-pointing or right-pointing arrow) presented prior to the appearance of a target object indicates the likely location of this target (e.g., Posner, 1980). Following such cues, participants can orient their attention endogenously to the expected target location. Such endogenous shifts can also be induced by instructing participants to move their attention in a particular direction (e.g., clockwise) between individual objects (e.g., Horowitz, Wolfe, Alvarez, Cohen, & Kuzmova, 2009; Jenkins, Grubert, & Eimer, 2018; Wolfe, Alvarez, & Horowitz, 2000). In these tasks, attention shifts are controlled in a fully voluntary fashion, irrespective of the visual properties of objects at attended versus unattended location.

A different type of endogenous attention is involved when attention is guided by nonspatial task sets. In visual search tasks, observers know which target to look for (e.g., a red square) but the location of the target object among distractors is uncertain. In these tasks, representations of target-defining features (attentional templates, Duncan & Humphreys, 1989) can be activated during the preparation for an upcoming search episode. Once a search display is presented, these feature-based templates guide spatial attention in a top-down fashion toward objects with template-matching features (e.g., Wolfe & Horowitz, 2004; Wolfe & Horowitz, 2017). These attentional guidance processes are not fully voluntary because they are also controlled by the presence of a template-matching feature in a search display. To distinguish them from voluntary attention shifts that are elicited in response to spatial cues or verbal spatial instructions, these feature-guided shifts of attention have previously been described as "priority-driven" (Horowitz et al., 2009; see also Jenkins et al., 2018, for speed differences between priority-based and fully voluntary attention shifts). Priority-driven attention shifts are endogenous in the sense that they are not triggered in a bottom-up fashion by all visually salient stimuli irrespective of their task relevance, but only by objects that match a currently active top-down task set. This was demonstrated in experiments in which search displays were preceded by spatially uninformative singleton cues (e.g., Folk, Remington, & Johnston, 1992). When these cues matched the currently active target template, they captured attention, as reflected by faster reaction times (RTs) to subsequent targets at cued as compared with uncued locations. In contrast, no such effects were triggered by nonmatching cues. Analogous priority-driven attention shifts are responsible for the guidance of attention toward objects with target-matching features during visual search. Although it is important to distinguish these priority-driven shifts from the fully voluntary shifts associated with purely spatial task sets, the fact that they are contingent on participants having activated an endogenous feature-specific task set is the reason why they are usually classified as endogenous (as compared with purely salience-driven).

Shifts of visual attention to particular locations do not only affect behavioral responses but can also change the perceived positions of stimuli in visual space. This was demonstrated by Suzuki and Cavanagh (1997) in a series of experiments that documented the existence of attentional repulsion effects (AREs). In most of their experiments, peripheral abrupt-onset cue stimuli that are assumed to trigger exogenous shifts of spatial attention were followed by a central Vernier probe consisting of two line segments above and below fixation. Participants had to judge whether the top line was offset to the left or right relative to

the bottom line. They consistently perceived the top line to be further away from the cued location than it actually was, reflecting a systematic localization bias away from an attended location (i.e., repulsion). For example, when a pair of cues appeared in the top left and bottom right quadrants, the top line was judged to be displaced toward the right relative to the bottom line, even when these lines were objectively perfectly aligned. The mechanisms that produce such repulsion effects are not yet fully understood. Suzuki and Cavanagh (1997) speculated that shifts of attention either result in a lateral suppression of position-coding units outside the focus of attention, or in an adjustment of receptive field properties (recruitment or shrinkage) near the cued location. All three mechanisms would result in shifting the peak of the response distribution of units coding the position of Vernier lines away from the current focus of attention, but it remains unclear if any of these processes is responsible for the emergence of AREs.

The link between exogenous attention shifts and AREs has been confirmed in several studies. Systematic AREs were found not only with visual abrupt-onset cues (Suzuki & Cavanagh, 1997), but also when cues attracted attention because they contained a salient feature singleton (Pratt & Arnott, 2008), as well as by auditory cues (Arnott & Goodale, 2006). Thus it is clear that stimulus-driven involuntary shifts of attention produce perceptual repulsion phenomena in a wide variety of task contexts. However, it remains unclear whether analogous AREs can also be produced as a result of endogenous (i.e., priority-driven) attention shifts. Positive evidence for this was reported by Suzuki and Cavanagh (1997; experiment 4). Cue displays contained diagonally arranged pairs of cues that differed in shape (circles and squares). Participants were instructed to activate a feature-specific top-down task set by attending to one shape while ignoring the other. AREs were elicited only by the currently attended but not by unattended shape cues, despite the fact that these cues did not differ in terms of their bottom-up salience. These results provide clear evidence that priority-driven attention shifts controlled by feature-specific task sets can produce repulsion effects. However, less consistent results were obtained in experiments in which central spatial cues were used to activate endogenous spatial task sets. Cutrone, Heeger, and Carrasco (2018) observed clear AREs in a task in which these cues specified the locations of to-be-attended lateral rapid serial visual presentation (RSVP) streams. However, because of the bottom-up salience of the RSVP stimulation, it remains possible that exogenous spatial attention was involved. Petersson, Hilchey, and Pratt (2019) failed to find any ARE in a task in which central symbolic cues directed voluntary attention toward a pair of visual field locations.

Thus although it remains unclear whether AREs can be elicited as a result of voluntary attention

shifts signaled by spatial cues, the results reported by Suzuki and Cavanagh (1997; experiment 4) suggest priority-driven attention shifts guided by endogenous feature-specific task sets can produce reliable repulsion effects. If this is the case, such effects should also be observed under conditions in which task-irrelevant objects match a currently target-defining feature. Such objects will attract attention in a task-set contingent fashion (Folk et al., 1992), and these spatial attention shifts should then result in AREs similar to those observed in previous studies for exogenous attentional capture. This hypothesis was tested by Gozli and Pratt (2012). In their study, Vernier stimuli consisted of two rows of five vertical colored lines above and below fixation. The to-be-judged target line pair was defined by a specific color (e.g., red), thus requiring participants to activate a corresponding color-specific attentional template. Vernier displays were preceded by pairs of cues in two diagonal visual quadrants that either matched the target color for the Vernier task or one of the nontarget colors. Under these conditions, only target-matching cues should trigger task-set contingent attentional capture. If this type of capture can produce repulsion effects, these effects should be found only on trials with matching cues but not on trials in which cues matched the nontarget color. This prediction was not confirmed. Gozli and Pratt (2012) found AREs of similar size for both types of cues, regardless of whether these cues were presented in isolation (experiment 1), or together with two gray cues in the other two quadrants (experiment 2). These results suggest that repulsion effects are not elicited following priority-driven attention shifts that are contingent on currently active endogenous feature-specific task sets. In a third experiment, they demonstrated that the same sets of color cues elicited clear contingent attentional capture effects for RTs to subsequent color-defined targets (analogous to Folk et al., 1992). Thus the activation of color-specific task sets systematically affected behavioral performance but not perceptual location judgments (i.e., AREs), suggesting that these two measures reflect qualitatively different types of attentional selection mechanisms.

The conclusion by Gozli and Pratt (2012) that the ARE is insensitive to task-set contingent attentional capture by target-matching colors is puzzling, given that Suzuki and Cavanagh (1997; experiment 4) found clear AREs in a feature-guided attentional selection task. The possibility remains that the AREs observed by Gozli and Pratt (2012) in response to both target-matching and target-nonmatching cues may have primarily reflected salience-driven exogenous attention shifts, which could have masked any additional residual effects of priority-guided attention. In their first experiment, cue displays contained pairs of abrupt-onset cues, which are known to trigger exogenous AREs (e.g., Suzuki & Cavanagh, 1997), irrespective of whether they match

the current target color. In their second experiment, these color cues were accompanied by a pair of gray cues, but the luminance level of the color cues was higher, rendering them more salient, and thus more able to attract attention in a bottom-up fashion. Under such circumstances, AREs may have been primarily the result of stimulus-driven exogenous attentional capture that was triggered in a similar fashion by both types of color cues. To obtain more conclusive evidence for the presence versus absence of links between feature-guided attention shifts and AREs, procedures have to be used that avoid a possible role of exogenous attention shifts in the emergence of such effects. The goal of the present study was to investigate these links under conditions that prevent any salience-driven attentional capture by template-matching or mismatching cues. In Experiment 1, standard behavioral measures of AREs were employed. In Experiment 2, these measures were combined with online electrophysiological markers of attentional capture by color cues.

We used a modified version of the ARE paradigm developed by Gozli and Pratt (2012). Vernier probe displays contained two pairs of lines (one vertical pair, one horizontal pair) in two different colors (see Figure 1). Prior to each block, one of the two colors was defined as the target color, and participants had to report the perceived displacement (clockwise or counterclockwise) within the target-color line pair. These probe displays were preceded by cue displays containing eight filled disks arranged in a circular fashion. In singleton cue displays, one of these disks was colored (either matching the target or the nontarget color) and the other seven were gray. To eliminate any salience differences between color cues and gray cues associated with a difference in luminance levels, all cue display stimuli were equiluminant. If this factor was responsible for the presence of AREs for both target-matching and target-nonmatching cues in Gozli and Pratt (2012; Experiment 2), these effects should now only be observed for target-color cues but not for nontarget-color cues. However, the possibility remains that despite being equated for luminance, a color singleton cue presented among uniform gray cues might still attract attention and elicit AREs in a primarily exogenous fashion (e.g., Pratt & Arnott, 2008), irrespective of its color. For this reason, a critical third double cue display condition was included. These double cues contained both a target-color and a nontarget-color disk in the two quadrants adjacent to the critical target test line among six gray circles. Because these two color cues are equally salient, and thus equally likely to trigger salience-driven exogenous attention shifts, any AREs that are specific to the location of the target-matching cue will thus necessarily reflect the impact to priority-driven color-guided attention shifts. For all types of color
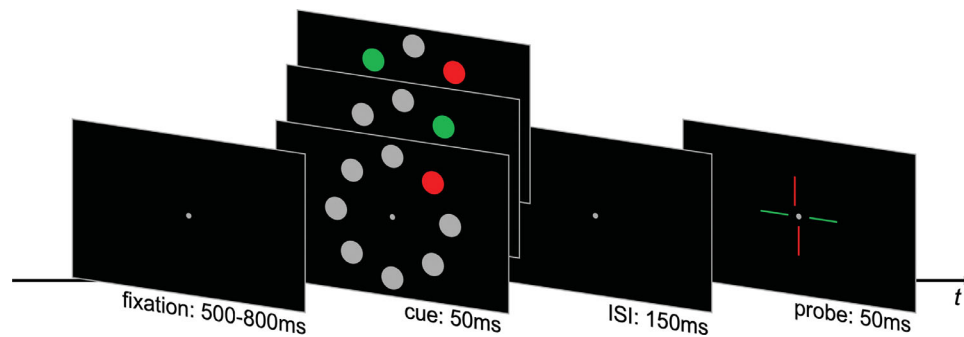
Figure 1. Example trial sequence (not to scale). On each trial, a single (target color or nontarget color) or double cue (target color and nontarget color) among a circular array of filled gray disk was followed by a probe, consisting of one test line among three nontest lines. The test line always appeared in the target color (in this case red) at one of three possible positions: −0.15°, 0°, 0.15°, whereas the nontest lines appeared centered (0°). Participants' task was to report the directional displacement (clockwise or counterclockwise) of the test line. ISI, interstimulus interval.

cues, the size of repulsion effects was quantified on the basis of participants' judgments of clockwise versus counterclockwise positional displacements relative to the location.

Experiment 1

Methods

Participants

Twenty naive participants were recruited to participate in Experiment 1. Five participants were excluded because eye tracking revealed a high percentage of trials with breaks of central fixation and eye blinks (>15% of all trials). For the remaining 15 participants (9 women, $M_{age} = 24.5$ years, $SD_{age} = 4.7$), trials with breaks of fixation and blinks (average across participants: 5.86% of all trials) were excluded from further analyses.

To calculate the sample size for this study, we performed a power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). This analysis was based on the critical parameters of the ARE (probe at 0°, $Diff = 0.12$, $SD = 0.13$), as determined in experiment 1 of Baumeler and Born (2019). This analysis showed that a sample size of 15 participants was needed to achieve a power of 0.95.

Apparatus and stimuli

The experiment was created and executed in MATLAB (The MathWorks Inc., Natick, MA) using the Psychophysics and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002). All stimuli appeared against a black background and were displayed on a 24-in. BenQ monitor

(60 Hz; 1920 × 1080 screen resolution) attached to a SilverStone PC, at a viewing distance of 55 cm. All stimulus colors were equiluminant (14 cd/m^2), as measured by a luminance meter (Konica Minolta CS-100A, Tokyo). Eye movements were recorded monocularly (left eye) using an EyeLink1000 Plus desk-mounted eye tracker with a remote infrared video-oculographic system (SR-Research Ltd., Ottawa, Canada) at a sampling rate of 1000 Hz. Manual responses were entered via a standard computer keyboard.

Procedure

Throughout each block a central fixation point (0.1° in diameter) was continuously present. Each trial started with a variable fixation interval of 500 to 800ms, followed by a cue display (50 ms duration). After an interstimulus interval of 150 ms, a probe display was presented (50 ms duration). Thus the cue-probe stimulus onset asynchrony was 200 ms. Forced-choice responses regarding the perceived displacement of the critical line (clockwise/counterclockwise) were required, and there was no time limit for response execution. In case of breaks of fixation (gaze coordinates outside of ±1.5°) or blinks, feedback was given on the screen after the response was executed (the words "FIXATION" or "BLINK" presented at the center of the screen for 1000 ms). The interval between the offset of the response or feedback display and the onset of the next fixation display was 800 ms.

Prior to each block, a specific target color feature was defined (red or green) by instructing participants to only report the perceived directional displacement (clockwise or counterclockwise) of the test line containing the predefined color feature. This task-relevant color was swapped after two blocks, and the task-relevant color for the first two blocks was counterbalanced across participants.
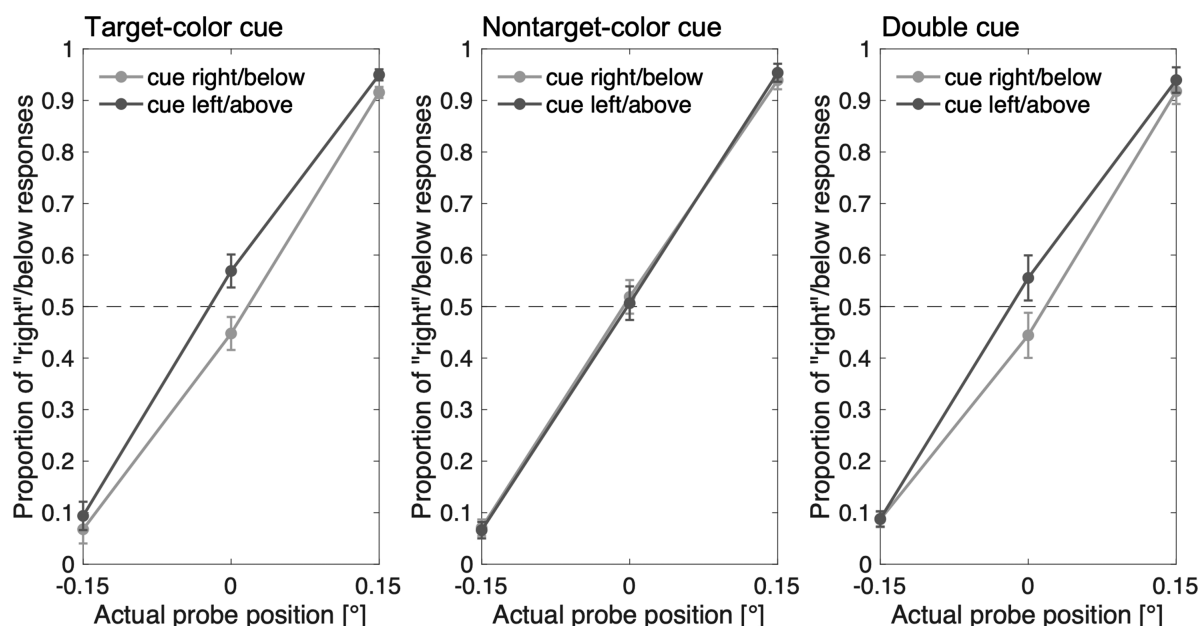
Figure 2. Proportion of "right"/below responses for cue sides right/below and left/above at each probe position, separate for all three cue conditions, target-color cue, nontarget-color cue, and double cue averaged across all 15 participants. Error bars represent 95% confidence interval of comparison cue right/below versus cue left/above. If error bars do not overlap, the difference is significant.

The cue display consisted of a circular array of eight sets of filled disk (1° in diameter), presented at a constant distance of 4.95° from central fixation. There were three cue display conditions. On two types of singleton cue trials, one disk was colored, and the other disks were gray. The color singleton was either presented in the target or in the nontarget color. It appeared randomly and equiprobably in one of the two quadrants adjacent to the subsequently presented critical target-color test line (discussed later). On double cue trials, cue displays contained one red and one green disk among six gray disks. The colored disk appeared in the two quadrants adjacent to the subsequently presented critical target-color test line, and these quadrants were counterbalanced across trials.

The probe display included two vertical (1° × 0.1°) and two horizontal (0.1° × 1°) lines occurring 2.5° from the fixation point. The vertical lines and horizontal line pairs always appeared in different colors (vertical red/horizontal green, or vice versa, counterbalanced across trials). The two nontarget-color lines were always fully aligned with each other and the fixation point (0°). One of the two target-color lines was also aligned with fixation, whereas the location of the other (critical) target-color line was manipulated. This line appeared with a displacement of –0.15° (25% trials), 0° (no displacement; 50% trials), or 0.15° (25% trials), with negative values indicating a displacement toward the left or the top.

Each participant completed 768 trials separated into four blocks. Trials with target-color singleton

cues, nontarget-color singleton cues, and double cues appeared in random order and with equal probability (256 trials per cue condition). An example trial sequence is illustrated in Figure 1.

Results

If a specific color cue triggers an ARE, this should be reflected by a higher proportion of perceived rightward or downward shifts of the critical target-color probe line following cues presented to the left of or above this line, relative to cues presented to the right of or below the line. We used participants' "clockwise/counterclockwise" judgments on individual trials to classify the direction of the perceived displacement of this line relative to the other target-color line on each trial (leftward/rightward for vertical and test lines; upward/downward for horizontal lines). AREs were quantified as the difference between the proportions of "right"/below responses for trials in which cues appear to the right/below versus to the left/above the critical test line. In the double cue condition, these proportions were calculated relative to the target-color cue. Figure 2 shows the proportions of perceived rightward/downward displacements for trials with cues right/below or left/above the critical test line. These results are presented separately for the three different objective probe displacements (–0.15°, 0°, and 0.15°), all three cue display conditions (target-color singleton cue, nontarget-color singleton cue, and

double cue), and both cue positions (right/below and left/above)[1]. For double cue displays, cue position refers to the relationship between the target-color cue and the subsequent critical target-color probe.

As can be seen in Figure 2, a clear ARE was present for probe displays without an actual offset (0°) that were preceded by target-color and double cues. Importantly, no such effect was found for nontarget-color cues. There was little evidence for an ARE on trials in which the two target-color probe lines were objectively nonaligned (–0.15° and 0.15°; see also Baumeler & Born, 2019). Paired-samples *t*-test comparing the effect of cue position (right/below vs. left/above) on judgments for nonaligned probes indeed confirmed that no repulsion was induced for test probe lines presented at –0.15° or 0.15°, all $ts(14) < 1.03$, $ps > 0.319$, $d < 0.27$, apart from a small but reliable ARE for target-color probe lines presented at 0.15° following a target-color singleton cue, $t(14) = 2.99$, $p = 0.010$, $d = 0.77$. To facilitate further analyses, differences in the induced ARE, were only analyzed for critical test lines presented with no actual offset (0°).

The main analyses therefore focused on probe location reports in trials with objectively aligned target-color probe pairs. Proportions of "right"/below responses were analyzed in a 3 (cue condition: target-color cue, nontarget-color cue, or double cue) × 2 (cue position: right/below or left/above) repeated-measures analysis of variance (ANOVA). The main effect of cue condition did not reach significance[2], $F(1.83, 25.59) = 0.46$, $p = 0.622$, $\eta_p^2 = 0.03$, but a significant main effect of cue position was observed, $F(1, 14) = 8.92$, $p = 0.010$, $\eta_p^2 = 0.39$. When a cue was presented on the left/above, test probe lines were perceived more toward the right/below as compared with trials in which the cue was presented on the right/below ($M_{left/above}$: 0.54, $M_{right/below}$: 0.47; higher values denote higher proportions of "right"/below responses). This demonstrates the presence of an ARE in Experiment 1. However, and importantly, a significant interaction between cue condition and cue position, $F(1.81, 25.32) = 6.16$, $p = 0.008$, $\eta_p^2 = 0.31$, indicated that this ARE differed between different cue display types. Follow-up paired-samples *t*-test showed that cue positions affected perceptual reports on trials in which target-color cues were presented, $M_{diff} = 0.12$, $t(14) = 3.93$, $p = 0.002$, $d = 1.01$, and also on trials with double cues, $M_{diff} = 0.11$, $t(14) = 2.72$, $p = 0.017$, $d = 0.70$. In contrast, no such ARE was found for trials with nontarget-color cues, $M_{diff} = 0.01$, $t(14) = 0.39$, $p = 0.704$, $d = 0.10$. To assess whether the size of this effect differed between target-color and double cues, an additional ANOVA was conducted for these two cue display conditions only. There was no evidence for any interaction between cue condition and cue position, $F(1, 14) = 0.03$,

$p = 0.856$, $\eta_p^2 = 0.01$, indicating that AREs of equivalent size were elicited by both types of cues.

Experiment 2

The presence of AREs on trials with target-color and double cues in Experiment 1, and the absence of such effects for nontarget-color cues, provides clear evidence that AREs are elicited as a result of attention shifts that are contingent on a current color-specific task set. Although AREs were reliably present at the group level for target-color and double cue displays, there was also considerable interindividual variability in the size of these effects (as illustrated in Figure 3, left panel). This shows that the ability of target-color cues to trigger repulsion effects differs considerably across participants. If these effects are the result of feature-guided shifts of attention toward target-color cues, differences in the magnitude of AREs across participants should be associated with individual differences in the susceptibility to attentional capture by these cues. The goal of Experiment 2 was to investigate this possibility by combining behavioral measures of cue-induced repulsion effects with independent electrophysiological markers of cue-induced attentional capture.

Procedures were similar to Experiment 1, except that target-color cue displays were presented on 75% of all trials, and nontarget-color cue displays on the remaining 25%. No double cue displays were included. Based on the findings of Experiment 1, we predicted that target-color cues should elicit behavioral repulsion effects, whereas no such effects should be found for nontarget-color cues. To measure the ability of target-color cues to attract attention, electroencephalogram (EEG) was recorded during task performance, and N2pc components were computed in response to target-color cue displays. The N2pc is an event-related brain potential (ERP) component that is assumed to reflect the allocation of attention to objects with target-defining features in multistimulus displays. It is typically elicited between 200 and 300 ms after display onset, as an enhanced negativity over posterior scalp electrodes contralateral to the side of where this object is presented (Eimer, 1996; Luck & Hillyard, 1994). Notably, in tasks in which target stimuli are preceded by task-irrelevant cue displays, an N2pc is elicited by cue display objects that match the current target-defining feature, demonstrating that these objects capture attention in a task-set contingent fashion (e.g., Eimer & Kiss, 2008). Therefore reliable N2pc components should also be triggered by target-color cues in Experiment 2. The critical question was whether the size of these cue-induced N2pc components for individual participants would predict the magnitude
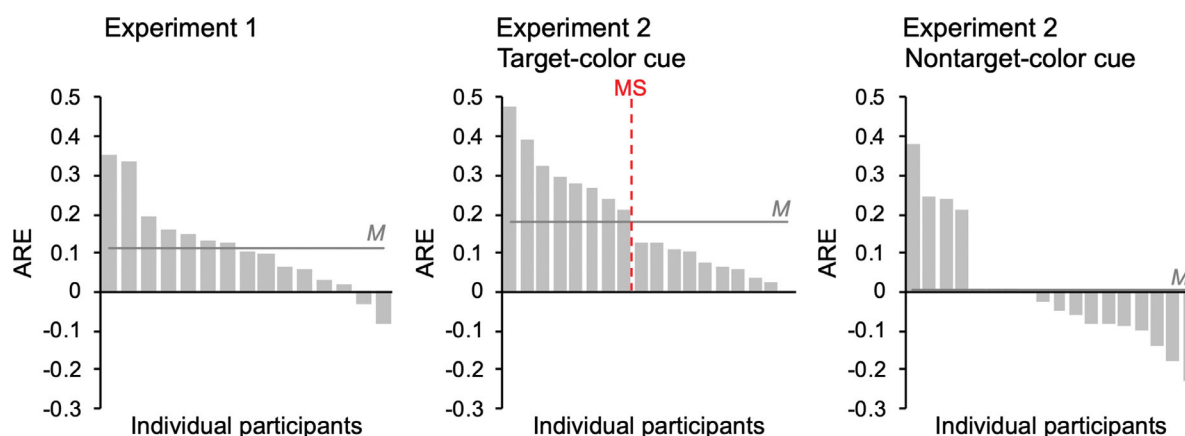
Figure 3. Size of the ARE for individual participants. Differences of "right"/below responses between trials with cues left/above versus right/below the critical test lines are shown from left to right for participants with larger versus smaller AREs. Positive values designate a perceived repulsion. The dark gray line indicates the mean (M) ARE across participants. Left panel: results from Experiment 1, averaged across target-color and double cue displays. Right panel: results from trials with target-color and nontarget-color cues in Experiment 2. The red dashed line indicates the median split (MS) boundary separating the two groups of participants with large versus small AREs for target-color cue trials in Experiment 2.

of individual repulsion effects observed for these participants. If AREs are the result of feature-guided attention shifts toward these cues, participants who are more susceptible to this type of attentional capture (as reflected by large N2pc components to target-color cues) should produce strong repulsion effects, whereas these effects should be weaker for participants who show less attentional capture (i.e., smaller cue-induced N2pc components).

Methods

Participants

Twenty-four new participants were recruited to participate in Experiment 2. Two participants had to be removed due to an inability to understand the task instructions, and four participants were excluded because of high proportions of EEG artefacts ($>30\%$) across all trials (see later for details). Eighteen participants (9 women, $M_{age} = 26.4$ years, $SD_{age} = 6.6$) remained in the sample.

Apparatus, stimuli, and procedure

These were identical to Experiment 1, with the following exceptions: no eye tracking with the EyeLink system was employed. Instead, eye gaze was monitored by recording the horizontal electrooculogram (HEOG). Only singleton cue displays were presented. On 75% of all trials, these displays contained a target-color cue. On the remaining 25%, a nontarget-color cue was presented. Because Experiment 1 showed that AREs

were primarily elicited on trials with aligned test lines, 90% of all trials included nondisplaced critical test lines (0° displacement). These lines were offset by –0.15° or 0.15° on the remaining 10% of all trials, with equal probability. Each participant completed 768 trials separated into 12 blocks. The task-relevant color that defined the to-be-judged test lines remained constant for six blocks and was swapped for blocks seven to 12.

EEG recording and data analyses

EEG activity was Direct current (DC)-recorded from 27 scalp sites: Fpz, F7, F8, F3, F4, Fz, FC5, FC6, T7, T8, C3, C4, Cz, CP5, CP6, P9, P10, P7, P8, P3, P4, Pz, PO7, PO8, PO9, PO10, and Oz. HEOG was recorded from linked electrodes placed at the outer canthi of the left and right eye. Data were collected at a sampling rate of 500 Hz, with a 40 Hz low-pass filter. No other offline filters were applied. Channels were referenced online to an electrode attached to the left earlobe and re-referenced offline to an average of both earlobes. Trials were epoched into 600 ms segments, from 100 ms before to 500 ms after cue display onset. Segments containing eye-movements (±30 μV in the HEOG channels), eye blinks (±60 μV at Fpz), and movement-related artifacts (±80 μV at all other channels) were rejected. Four participants were excluded from analyses because of trial rejection rates exceeding 30%. For the remaining participants, average trial rejection percentage was 8.94%. ERP analyses were focused on the majority of trials in which target-color cue displays were followed by aligned critical test lines (0° displacement). For these trials, EEG was averaged relative to a 100 ms precue baseline. N2pc
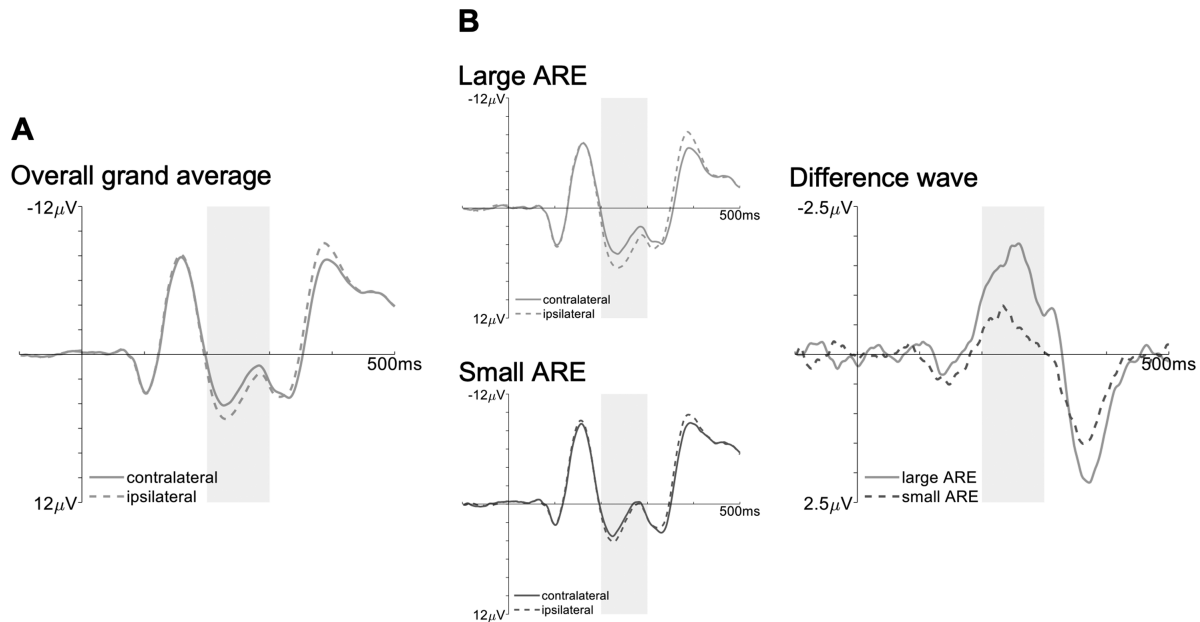
Figure 4. N2pc components triggered by target-color cues. (A) Grand average ERPs obtained at lateral posterior electrode sites PO7/PO8 contralateral and ipsilateral to the side of the color cue during the 500 ms interval following cue display onset, relative to a 100 ms baseline. (B) Grand average ERPs, shown separately for participants with large versus small AREs, together with the corresponding N2pc difference waveforms (computed by subtracting ipsilateral from contralateral ERPs) for both groups.

mean amplitudes were quantified based on ERP mean amplitudes obtained in the 200 to 300ms interval after cue display onset at lateral posterior electrode sites PO7 and PO8 contralateral and ipsilateral to the position of the target-color cue.

Results

Behavioral results

Analogous to Experiment 1, no AREs were present for nonaligned probes preceded by target-color cues (positions –0.15° and 0.15°; $ts(17) < 1.41$, $ps > 0.177$, $d < 0.33$). Therefore proportions of "right"/below responses were only analyzed for trials with 0° probe displacement, in a 2 (cue condition: target-color cue or nontarget-color cue) × 2 (cue position: right/below or left/above) repeated-measures ANOVA. Results were essentially identical to Experiment 1. There was no significant effect of cue condition, $F(1, 17) = 1.23$, $p = 0.238$, $\eta_p^2 = 0.07$. However, a main effect of the cue position, $F(1, 17) = 8.50$, $p = 0.010$, $\eta_p^2 = 0.33$, confirmed the presence of a repulsion effect, with probe lines perceived as more displaced toward the right/below on trials with left/above cues as compared with right/below cues ($M_{\text{left/above}}$: 0.55, $M_{\text{right/below}}$: 0.46). Critically, this effect interacted with cue condition, $F(1, 17) = 20.44$, $p < 0.001$, $\eta_p^2 = 0.55$. Follow-up paired-samples t-tests demonstrated that a significant ARE was elicited only by target-color cues,

($M_{diff} = 0.17$; $t(17) = 5.17$, $p < 0.001$, $d = 1.22$), but not by nontarget-color cues ($M_{diff} = 0.02$; $t(17) = 0.48$, $p = 0.637$, $d = 0.11$).

N2pc components to cue displays

Figure 4A shows ERPs elicited in response to target-color cue displays in the 500 ms interval following the onset of the cue displays at electrodes PO7/PO8 contralateral and ipsilateral to the side where these color cues were presented. Target-color cues triggered reliable N2pc components, reflected by larger negative amplitudes at contralateral versus ipsilateral electrodes in the 200 to 300ms interval after cue display onset, $M_{diff} = -0.92\mu$V, $t(17) = -4.94$, $p < 0.001$, $d = 1.16$. This demonstrates that target-color cues attracted attention.

Next, we investigated whether differences in the size of repulsion effects between individual participants were associated with individual differences in the susceptibility of attentional capture by these cues. Participants with large versus small AREs were separated with a median split, based on the proportion of "right"/below responses on trials with left/above versus right/below target-color cues (see Figure 3, right panel). As shown in Figure 4B, N2pc components to target-color cues were indeed substantially larger for participants with large as compared with small repulsion effects. This was confirmed in a repeated-measures mixed 2 × 2 ANOVA of N2pc mean amplitudes measured in
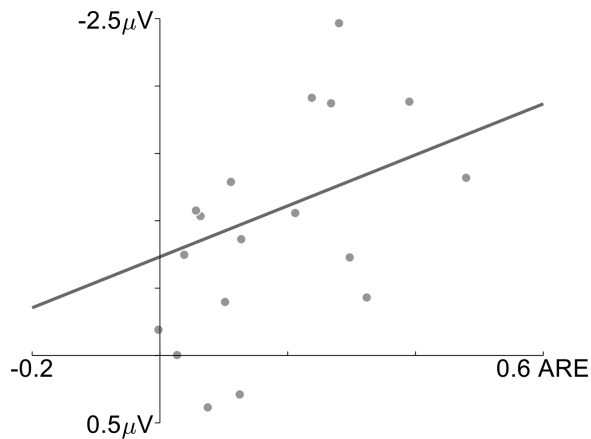
Figure 5. Association between the magnitude of AREs and mean amplitudes of N2pc components triggered by target-color cues across individual participants ($r = -0.547$, $p = 0.019$).

the 200 to 300 ms poststimulus time window, with the factors group (large ARE or small ARE) and laterality (electrode ipsilateral or contralateral to the target-color cue). There was no significant main effect of the between-subject factor group, $F(1, 16) = 2.97$, $p = 0.104$, $\eta_{\mathrm{p}}^2 = 0.16$. A main effect of laterality, $F(1, 16) = 36.56$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.70$, confirmed the presence of cue-induced N2pc components. Critically, there was a significant interaction between group and laterality, $F(1, 16) = 9.52$, $p = 0.007$, $\eta_{\mathrm{p}}^2 = 0.37$, reflecting the N2pc amplitude difference between the two groups shown in Figure 4B. Follow-up paired-samples t-tests comparing contralateral and ipsilateral ERPs separately for both groups showed that a reliable cue-induced N2pc was present for the group of participants with large AREs, $M_{\mathrm{diff}} = -1.39 \mu$V, $t(8) = 6.17$, $p < 0.001$, $d = 1.99$. In contrast, the mean N2pc amplitude observed for the group with small ARE was much smaller, $M_{\mathrm{diff}} = -0.45 \mu$V, and the contralateral-ipsilateral difference only approached significance $t(8) = 2.19$, $p = 0.069$, $d = 0.68$.

To further test whether this link between the size of N2pc components to target-color cues and the size of AREs at the group level can also be demonstrated across individual participants, we correlated the magnitude of repulsion effects for individual participant with the mean amplitudes of N2pc components measured for each participant. As shown in Figure 5, these two measures were indeed associated, and the correlation between them was reliable ($r = -0.547$, $p = 0.019$).

Nontarget-color cue displays were presented on only 25% of all trials. These cue displays did not trigger significant behavioral repulsion effects across all participants. There was considerable interindividual variability, with some participants showing positive and others negative AREs following nontarget-color cues (see Figure 3, right panel). For completeness, we also

computed N2pc components elicited by these displays. A comparison of ERPs elicited contralateral and ipsilateral to the side of a nontarget-color cue in the 200 to 300 ms interval after cue display onset showed that these cues also triggered a reliable N2pc component, $M_{\mathrm{diff}} = -0.71 \mu$V, $t(17) = -5.38$, $p < 0.001$, $d = 1.28$. The size of nontarget-color cue N2pc amplitudes for individual participants tended to be associated with the magnitude of AREs in response to these cues, but this correlation only approached significance ($r = -0.429$, $p = 0.075$). There was no significant correlation between individual N2pc amplitudes in response to nontarget-color cues and the size of repulsion effects elicited on trials with target-color cues ($r = -0.220$, $p = 0.379$).

Discussion

Previous research has demonstrated that AREs can be triggered as a result of exogenous salience-driven attentional capture (e.g., Suzuki & Cavanagh, 1997; Arnott & Goodale, 2006; Pratt & Arnott, 2008). Here we investigated whether an analogous perceptual effect is also elicited as a result of priority-driven shifts of attention, in which attention is selectively allocated to visual objects that match a currently active feature-specific endogenous task set. Although Suzuki and Cavanagh (1997; experiment 4) found evidence for a link between such feature-guided attention shifts and repulsion effects, results reported by Gozli and Pratt (2012) suggest that AREs are not sensitive by priority-driven feature-guided shifts of attention.

In the current study, we found clear support for the hypothesis that repulsion effects are elicited as the result of priority-driven attention shifts. In Experiment 1, single-color cue displays produced AREs only when the cues matched the currently relevant target color, whereas repulsion effects were entirely absent on trials in which cues appeared in a nontarget color. This result, which was replicated in Experiment 2, is obviously inconsistent with the findings by Gozli and Pratt (2012), who observed reliable AREs for both types of cues, both when these cues were presented in isolation and when they were accompanied by additional gray objects in the same display. In contrast to this previous study, in which pairs of identical color cues appeared simultaneously in diagonal visual quadrants, target-color and nontarget-color cue displays contained only a single colored object that appeared among seven gray disks (see Figure 1). More importantly, the colored and gray cue display objects were always equiluminant, whereas the color cues had higher luminance values and were thus more salient than the gray items in the study by Gozli and Pratt (2012). Here the color cues may have attracted attention in an exogenous salience-driven

fashion, irrespective of whether they matched the current target color. The present results demonstrate that when this luminance factor is controlled, repulsion effects are elicited in a task-set contingent fashion, only by objects that match the currently relevant target color.

Further strong evidence for this conclusion was found in Experiment 1 in trials with double cue displays that contained a target-color and a nontarget-color cue in adjacent quadrants. On these trials, clear AREs were triggered relative to the location of target-color cues, and the magnitude of these repulsion effects was the same as in response to cue displays that contained only a single target-matching cue. Because these double cue displays contained two equally salient color singleton objects among six gray disks, any perceptual repulsion cannot be due to purely salience-driven exogenous attentional capture. This effect thus exclusively reflects the impact of priority-driven attention shifts that are triggered because a feature-specific endogenous task set is currently active.

Because the magnitude of the repulsion effects observed in Experiment 1 varied considerably across participants (see Figure 3, left panel), Experiment 2 tested whether this interindividual variability was due to individual differences in the ability of target-color cues to attract attention. N2pc components were measured as ERP markers of attentional capture by these cues, to find out whether N2pc amplitudes measured for individual participants were associated with the magnitude of AREs reported by these participants. This was indeed the case. N2pc components were reliably larger for the group of participants that showed large repulsion effects relative to the group with small AREs. In addition, there was also a reliable correlation between individual N2pc amplitudes to target-color cues and individual AREs. This pattern of results strongly suggests that the magnitude of the repulsion effect for an individual participant reflects their specific susceptibility to task-set contingent attentional capture by target-color cues. In other words, individuals who have a stronger tendency to shift attention toward objects with target-matching features will show larger repulsion effects in response to these objects. The presence of this correlation also provides additional evidence that repulsion effects on perceptual judgments can arise as the result of attention shifts that are guided by currently active feature-selective top-down task sets.

As AREs and N2pc amplitudes to target-color cues were found to be correlated across participants, we also explored whether analogous links might also exist within participants, across different trials. For each participant, perceptual judgments on trials with target-color cue displays were classified as either showing or not showing a repulsion effect (i.e., a perceived displacement in the uncued versus cued direction), and N2pc components were computed for both types of trials. No N2pc amplitude differences

were found between these trials.[3] This indicates that in contrast to interindividual differences, trial-by-trial variations in the amount of attentional capture by target-color cues for each participant are not associated with differences in attentional repulsion.

It is notable that in both experiments, AREs were entirely absent on trials with nontarget-color cue displays. This may seem surprising, given that these displays contained one color singleton disk among seven uniform gray disks, and the known ability of feature singletons to attract attention in an exogenous salience-driven fashion. Furthermore, Pratt and Arnott (2008) have previously shown that salient color singleton cues can trigger perceptual repulsion effects, although these effects were smaller than those observed for other types of salient cues (onset-offset stimuli). In contrast to the present study, the participants tested by Pratt and Arnott (2008) did not have a color-specific task set, and the AREs observed for color singleton cues may therefore have reflected exogenous attention shifts that arise in the absence of color-selective attentional guidance. Previous behavioral and ERP studies of task-set contingent attentional capture have demonstrated that when such task sets are activated, salient but task-irrelevant singletons no longer capture attention (e.g., Eimer & Kiss, 2008; Folk et al., 1992). The presence of an attentional set for a specific target color may have prevented the emergence of repulsion effects in response to nontarget-color cues in the present experiments. However, it is important to note that even though these cues did not produce any AREs at the group level, they triggered reliable N2pc components in Experiment 2, indicative of some salience-driven attentional capture (see also Eimer & Kiss, 2008, for the presence of reliable albeit small and delayed N2pcs in response to such cues). Furthermore, there was a tendency for N2pc amplitudes to nontarget-color cues to be associated with perceptual judgments (i.e., participants with larger N2pcs tended to show typical repulsion effects, whereas smaller N2pcs were linked to an atypical attraction, resulting in the absence of an overall ARE to nontarget-color cues across all participants). These observations suggest that nontarget-color singleton cues did attract exogenous attention to some degree. This may have had a limited impact on perceptual judgments, which was, however, much less pronounced than the systematic and strong effects of the task-set contingent attention shifts elicited by target-color cues.

Conclusions

Overall, the present study has demonstrated that AREs on perceptual judgments can be triggered as a consequence of priority-based attention shifts that

are elicited in a feature-specific fashion in line with currently active top-down task sets. This confirms earlier findings from Suzuki and Cavanagh (1997), but contradicts previous claims that such repulsion effects are insensitive to feature-guided attentional control (Gozli & Pratt, 2012). We also provide the first direct demonstration, to our knowledge, with online electrophysiological markers that repulsion effects are indeed attentional in nature. By measuring attentional capture in response to cue displays and attentional repulsion to test displays independently, we were able to show that perceptual repulsion effects are the result of attention shifts to specific object locations that take place prior to the presentation of the stimuli that have to be perceptually judged.

Keywords: attentional repulsion effect, attentional control, event-related potentials, N2pc, visual attention

Acknowledgments

Footnotes

[1] Datasets for horizontal and vertical target-color probe orientations were collapsed. In an ANOVA that included the same factors as in the ANOVA reported later plus the additional factor probe orientation, neither the main effect probe orientation nor any interactions involving this factor reached significance, $Fs(1.99, 27.79) < 1.54$, $ps > 0.232$, $\eta_p^2s < 0.10$.

[2] For all experiments, Greenhouse-Geisser corrected values were reported if the assumption of sphericity was violated.

[3] The analysis of N2pc mean amplitudes obtained a main effect of laterality, $F(1, 17) = 22.41$, $p < 0.001$, $\eta_p^2 = 0.56$, reflecting the presence of cue-induced N2pcs, but no interaction with trial type, $F(1, 17) = 0.96$, $p = 0.342$, $\eta_p^2 = 0.05$.

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