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The guidance of attention by templates for rejection during visual search

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ABSTRACT

The hypothesis that foreknowledge of nontarget features in visual search is represented by negative search templates ('templates for rejection') that facilitate attentional guidance remains disputed. In five experiments, we investigated this proposal by measuring search performance and electrophysiological markers of target selection (N2pc components) and nontarget suppression (P_D components). We compared search tasks where positive or negative cues signaled the color of targets or nontargets, respectively, and tasks with neutral non-informative cues. Positive cues elicited performance benefits relative to neutral cues. Negative cues produced behavioral and electrophysiological costs for target selection, and some evidence for the inhibition of negatively cued nontargets, but there was no support for the proposal that these items initially attract attention. Performance costs for negative cues dissipated after practice with the same negatively cued nontargets for approximately 25-50 trials, and eventually turned into benefits after several hundreds of trials. However, the emergence of negative cue benefits was not accompanied by electrophysiological evidence for faster or more efficient inhibition of nontargets, indicating that they are not produced by learned suppression mechanisms mediated by negative search templates. We conclude that templates for rejection do not facilitate search but normally interfere with target selection. Although negative cue benefits can be observed after extended exposure to the same nontarget features, these benefits do not reflect active attentional guidance, and are likely to be the result of passive habituation processes.

Keywords: Selective attention; top-down control; inhibition; visual search; event-related brain potentials

INTRODUCTION

During visual search, representations of known target features are utilized to guide attentional selection towards candidate target objects. These representations are referred to as attentional templates (e.g., Duncan & Humphreys, 1992) or attentional control settings (e.g., Folk, Remington, & Johnston, 1992), and are believed to be maintained in visual working memory (see Olivers, Peters, Houtkamp, & Roelfsema, 2011, for review). Templates are activated during the preparation for search (Grubert & Eimer, 2018), and elicit rapid biases in attention towards stimuli with template-matching features (e.g., Eimer & Kiss, 2008; Folk et al., 1992). Search templates can specify basic target features such as color or size (e.g., Eimer & Kiss, 2008), but can also represent feature combinations in an object-based fashion (e.g., Berggren & Eimer, 2018a). There is also evidence that multiple feature templates can be activated simultaneously (e.g., Grubert & Eimer, 2016; Irons, Folk, & Remington, 2012). While the role of such preparatory representations of target-defining attributes in the guidance of visual search is undisputed (e.g., Wolfe, 2007), it has recently been suggested that search templates may not only be employed to guide attention *towards* possible target objects, but also to guide attention *away* from distractors with known task-irrelevant features. However, the question whether such ‘negative templates’ (e.g., Reeder, Olivers, & Pollmann, 2017) or ‘templates for rejection’ (e.g., Arita, Carlisle, & Woodman, 2012) exist, and whether they play an important role in the control of visual search, remains controversial.

Several studies have demonstrated that knowledge about distractors can affect search under some conditions. Knowledge about distractor locations facilitates search performance and reduces distractor-specific neural processing (Van Morselaar & Slagter, 2019). When a salient singleton distractor is repeated in numerous successive search displays, performance improves and the frequency of eye movements towards this distractor decreases (e.g., Vatterot & Vecera, 2012; Gaspelin & Luck, 2018a; Gaspelin, Leonard, & Luck, 2017), suggesting that some form of feature-based distractor suppression can also be learned. This is also supported by the fact that evidence for learned suppression immediately disappears when the feature of distractor singletons suddenly changes (Vatterott & Vecera, 2012). Gaspelin and Luck (2018b) have proposed a signal suppression hypothesis that can account for such effects. According to this hypothesis, salient objects automatically trigger an “attend-to-me” signal that usually results in shifts of spatial

attention. However, this signal can be inhibited and attentional capture can be prevented by active inhibition processes. In studies supporting this hypothesis, distractor features remained constant across trials, indicating that repeated exposure is needed in order to be able to suppress signals from task-irrelevant singletons. One possibility is that this suppression is based on templates for rejection, and that the acquisition of these templates requires extensive training. An alternative possibility is that repetitions of distractor features facilitate search performance not through template-guided learned suppression, but as a result of habituating to repeated task-irrelevant features (see Chelazzi, Marini, Pascucci, & Turatto, 2019, for a discussion of the role of habituation mechanisms in distractor suppression).

The finding that extensive training is required before knowledge about distractor features can facilitate search performance contrasts markedly with results for ‘positive’ search templates for known target features, which will guide attention immediately once a new target-defining feature has been specified by a cue (e.g., Berggren, Nako, & Eimer, 2020; Grubert, Carlisle, & Eimer, 2016). This discrepancy is further highlighted by a study that employed similar cueing procedures to indicate the color of distractors in a visual search task (Moher & Egeth, 2012). Search performance was *worse* in this condition relative to a task where no such information was available. These authors proposed that instead of actively ignoring cued distractors, observers initially attended to them (the “white bear” effect), and supported this in a subsequent experiment using dot-probe cues (Moher & Egeth, 2012, Exp.3). Results of another experiment where color placeholders were presented prior to search displays (Moher & Egeth, 2012, Exp.4) suggested that this rapid capture of attention by cued distractor colors was later replaced by suppression. These observations suggest that participants employed a “search and destroy” strategy, where cued distractors had to be initially attended in order to be subsequently inhibited (see also Beck, Luck, & Hollingworth, 2018, for similar results with overt gaze behavior). These findings by Moher and Egeth (2012) strongly suggest that in contrast to positive target templates, cued negative templates do not produce immediate benefits for search performance. Either such negative templates do not exist at all, or they can only be formed as a result of longer-term learning.

However, another study (Arita et al., 2012) has reached the opposite conclusion, by providing evidence that negative templates can be activated on a trial-by-trial basis.

Participants had to find orientation-defined targets (Landolt-C rings with a gap at the top or bottom) in displays where items in one lateral hemifield appeared in one color, and items in the opposite hemifield in another color. Prior to each search display, positive, negative, or neutral color cues were presented, in different blocks. Positive cues specified the color of the items in the hemifield where the target was present, negative cues the color of the items in the opposite hemifield that did not include the target, and neutral cues a color that was not present in the search display. Faster reaction times (RTs) were found with positive as compared to neutral cues, and also, critically, for negative versus neutral cues, indicating that search could be guided both by positive as well as negative templates. This interpretation was subsequently challenged by Beck and Hollingworth (2015), who argued that the RT benefit observed by Arita et al. (2012) for negative cues was the result of a location-based strategy, where observers waited until the search display appeared, localized the side where items in the cued distractor color appeared, and then allocated attention to the opposite side. In support of this account, they found that negative cue benefits were eliminated in search displays where the positions of cued and uncued colors were randomly intermixed (see also Conci, Deichsel, Müller, & Töllner, 2019, for evidence that unlike RT benefits produced by positive cues, negative cue benefits are only found when search difficulty is high, suggesting qualitatively different mechanisms).

A way to obtain more direct insights into whether, when, and how preparatory templates for rejection affect attentional guidance mechanisms in visual search is to combine behavioral measures of search performance with on-line electrophysiological markers of target selection and distractor suppression mechanisms. Research using event-related potentials (ERPs) has shown that the N2pc component indicates the allocation of attention to objects with target-matching features in visual search displays. The N2pc is an enhanced negativity emerging approximately 180-200 ms post-stimulus at posterior electrode sites contralateral to the side of candidate target objects (e.g., Eimer, 1996; Luck & Hillyard, 1994), and reflects the enhancement of neural responses for objects with target-defining features within extrastriate ventral visual cortex (Hopf et al., 2000). Numerous previous studies have used the N2pc to track attentional guidance processes by positive target templates in real time (see Luck & Kappenman, 2011; Eimer, 2014, for reviews of the N2pc and its link to mechanisms involved in attentional selection during visual search). If negative templates are involved in the guidance of attention in visual search, this should be

reflected by systematic benefits (or costs) for N2pc components to search targets, relative to conditions where these templates are not available. Another lateralized ERP component is believed to be linked with distractor suppression. The distractor positivity (P_D component) is an enhanced positivity at posterior electrodes contralateral to the side of salient distractors (e.g., Hickey, Di Lollo, & McDonald, 2009; Sawaki & Luck, 2010), which has been linked to the active inhibition of “attend-to-me” signals triggered by such objects (Gaspelin & Luck, 2018b; see also Gaspar & McDonald, 2014, and Feldmann-Wüstefeld, Busch, & Schubö, 2020, for further evidence for links between the P_D and distractor suppression). If such inhibition processes were controlled by templates for rejection, the presence of P_D components should indicate that such templates are activated.

One recent experiment has employed N2pc components to investigate attentional allocation processes elicited when negative cues indicate distractor features in an upcoming search display. Carlisle and Nitka (2019, Exp.1) used the same paradigm as Arita et al (2012), with positive, negative, or neutral cues preceding search displays where items in two different colors appeared on opposite sides. Following positive cues, clear N2pc components were observed contralateral to the cued target hemifield, as expected. In blocks with negative cues, no N2pc was triggered contralateral to the cued side, but instead contralateral to the opposite uncued side where the target was located. This was interpreted as evidence against the “search and destroy” hypothesis proposed by Moher and Egeth (2012), as rapid attentional shifts towards items in the color specified by negative cues should have produced corresponding N2pc components. However, the absence of such an N2pc to negatively cued items can also be explained by a location-based strategy (Beck & Hollingworth, 2015), where observers identify the side of the items in the cued distractor color before shifting attention to the opposite side. In line with this possibility, Carlisle and Nitka (2019, Exp.1) observed a substantial delay of N2pcs contralateral to the target in blocks with negative as compared to positive cues. The additional fact that they also did not observe reliable RT benefits for negative as compared to neutral cues casts further doubt on the suggestion that search was guided by active attentional templates for suppression in negative cue blocks.

The goal of the current study was to employ behavioral and ERP markers of attentional selection and suppression to obtain more systematic insights into whether and how negative templates can be employed for the guidance of attention in visual search.

Analogous to Arita et al. (2012) and Carlisle and Nitka (2019), we employed a cueing procedure with negative, neutral, or positive cues, in different blocks. Search targets were Landolt squares with a gap at the top or bottom, and distractors had a gap on the left or right. Search displays contained four items in two different colors. Two of these items were presented on the vertical midline (above and below fixation) and two on the horizontal midline (to the left and right of fixation). In order to prevent any location-based hemisphere selection in response to cues (Beck & Hollingworth, 2015), one item in the cued color appeared on the vertical and the other on the horizontal midline, and the items in the other uncued color were presented at the two remaining vertical and horizontal locations (see Figure 1). In Experiment 1, a different color cue was presented on each trial. In positive cue blocks where cues indicated the upcoming target color, RTs were expected to be faster than in neutral cue blocks where the cues indicated a color that would not appear in the next search display. This RT benefit should be accompanied by earlier N2pc components to lateral targets, confirming that positive cues facilitate attentional target selection during visual search. The critical question was whether similar benefits relative to neutral cues would also be found in negative cue blocks where the cues indicated the color of the to-be-ignored distractors. Arita et al. (2012) found RT benefits for negative cues, which they attributed to the active guidance of search by templates for rejection. If this was correct, similar benefits should also be observed in Experiment 1 for negative as compared to neutral cue blocks, and these benefits should be mirrored by an earlier onset of target N2pcs in blocks with negative cues. In contrast, Moher and Egeth (2012) found RT costs for negative cues, indicating that negative cues interfere with the guidance of attention to search targets. If this was the case, such behavioral costs should also be observed in Experiment 1, and target N2pcs should be delayed in negative as compared to neutral cue blocks.

In addition to measuring N2pcs to search targets, we also measured lateralized ERP components in response to positively and negatively cued color nontargets, in order to find out whether they are selectively attended or ignored. We chose the horizontal/vertical search display stimulus arrangement in order to be able to measure N2pc components to these lateral nontargets, independently of any overlap with N2pcs that might be triggered simultaneously by a target object in the same display. Because the N2pc is a lateralized ERP component, it is only elicited by targets in the left versus right visual field, but not by target

objects on the vertical midline. Therefore, the allocation of attention to lateral nontargets that match the color of the preceding cue should result in reliable N2pc components in search displays where the target appeared above or below fixation. Such N2pcs should be observed for lateral nontargets that follow a matching positive cue. A critical question was whether an N2pc would also be present for negatively cued nontargets. If such items initially capture attention, as postulated by the “search and destroy” hypothesis (Moher & Egeth, 2012), they should trigger corresponding N2pc components. In contrast, if templates for rejection activated in response to negative cues immediately result in a top-down suppression of negatively cued distractors (Arita et al., 2012), no such distractor N2pc should be observed in negative cue blocks. Instead, suppression might be reflected by a P_D component to cue-matching distractors, which should again be visible on trials with vertical targets which do not elicit any concurrent N2pc component. If this suppression-related component was only elicited in response to physically salient feature singleton items (e.g., Sawaki & Luck, 2010), or only when the same distractor feature is repeated across successive trials (e.g., Gaspelin & Luck, 2018a), no P_D should be elicited by negatively cued color distractors in Experiment 1.

EXPERIMENT 1

Method

Participants

Twelve participants were initially recruited to participate in Experiment 1. Of these, two participants were excluded and replaced with new participant data due to a high number of trials with eye movement artifacts (> 60 %). Of the final sample (M age = 30 years, $SD = 6$; 7 male; 1 left-handed), all participants reported normal or corrected-to-normal vision. Sample size was determined on the basis of the only previous N2pc-based experiment that employed positive, negative, and neutral cues (Carlisle & Nitka, 2019, Exp.1). Based on the reported t -value for mean target N2pc amplitude differences between neutral and positive cue blocks in this experiment, with power at 0.8 and an alpha level of .05, analysis using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007) produced a recommended sample size of 12 participants was calculated. This is also in line with the sample size used in many previous N2pc studies on attentional selection in visual search.

Stimuli and Procedure

The experiment was created and run using E-Prime 2.0 software (Psychology Software Tools, Inc.). All stimuli were shown on a 24-inch BenQ monitor (60 Hz; 1920 x 1080 screen resolution) at a viewing distance of approximately 90 cm. The experiment was run on a SilverStone PC, and manual responses were recorded using a standard PC keyboard. All stimuli appeared on a black background with a gray fixation dot ($0.2^\circ \times 0.2^\circ$ of visual angle) shown constantly during a block. On each trial, a cue display was followed by a search display, as shown in Figure 1. Cue displays contained two square shapes ($0.83^\circ \times 0.83^\circ$) presented to the left and right of fixation at an eccentricity of 1.02° relative to the center of a shape. One shape was always gray (CIE color coordinates: .305/.325), and the other could be red (.605/.322), orange (.543,.409), green (.296/.604), blue (.169/.152), or magenta (.270/.134). The colored shape was equally likely to appear on the left or right side of fixation. Search displays included four colored outline squares (diameter: $0.89^\circ \times 0.89^\circ$; line width: 0.16°), each containing a small gap in one of its sides (width: 0.03°). Gap size was small in order to make target detection and discrimination difficult, so that participants were incentivized to use color cues. Square objects appeared directly above, below, left, and right of fixation at an eccentricity of 1.40° measured relative to the center of each square. Three of the four squares were nontargets that contained gaps in their left or right side (two squares with a left gap and one with a right gap, or vice versa, randomized across trials). The remaining square contained a gap in its top or bottom (target). Within each search display, two squares appeared in one color and two in another, selected from the same colors as for cue displays, with the exception of gray. The two squares on the vertical midline (above/below fixation) and the two squares on the horizontal midline (to the left/right of fixation) always differed in their color (see Figure 1).

Participants were instructed to search for the square with a gap in its top or bottom, and to indicate the location of the gap (top/bottom) by pressing the '2' or '0' keys on the numeric keypad with their right index or middle fingers, as quickly and as accurately as possible. Three blocked conditions were run. In the positive cue condition, participants were instructed that the color shown on one side of the cue display signaled the color of the upcoming search target object with 100% validity. In the negative cue condition, they were told that this color indicated the color of two nontarget objects in the upcoming search display, and that the target would always be shown in a different color. In these two

conditions, the information provided by the color cue effectively reduced search set size from four to two items. In the neutral cue condition, participants were told that the color shown in the cue display would be absent in the upcoming search display. No emphasis was placed on the utility of these different cues, and participants were encouraged to use them in the task as they would be “helpful to search”. At the start of each block, the word “positive”, “negative”, or “neutral” appeared in block capital letters, as a reminder of the type of cue for this block.

Each trial began with a cue display appearing for 100 ms, which was followed after a 700 ms inter-stimulus interval by a search display (100 ms duration). The interval between the offset of the search display and the onset of the cue display on the next trial was 1900 ms. Responses occurring outside the 2000 ms time interval following search display onset were coded as incorrect. Participants completed nine experimental blocks of 64 trials each. A brief practice block was run for each cue condition prior to the experimental blocks. Block order followed a Latin square design and was counterbalanced across participants. Within each block, targets appeared unpredictably and with equal probability at any of the four possible locations. The location of the nontarget that matched the target color was also counterbalanced within each block (e.g., when target was shown to left of fixation, the color-matching nontarget was equally likely to be above or below fixation). Cue color and the matching color of search display items were randomly chosen on each trial, as was the color of the other two items in the search displays.

Insert Figure 1 about here

EEG Recording and Data Analysis

EEG was DC-recorded at 27 scalp electrodes mounted on an elastic cap (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). A 500-Hz sampling rate was used with a 40 Hz low-pass filter. No other filters were applied offline. Channels were referenced online to an electrode attached to the left earlobe, and later re-referenced offline to the average of both earlobes. Incorrect-response trials, trials with eye blinks (over $\pm 60 \mu\text{V}$ at Fpz), eye movements (exceeding ± 30

μV in the HEOG channels), and movement-related artifacts (exceeding $\pm 80 \mu\text{V}$ in all other channels) were removed. These artifact rejection procedures resulted in the removal 28% of all epochs (averaged across participants, ranging from 11% to 57% for individual participants). ERPs elicited in response to search displays were computed for each cue condition, separately for trials where the target appeared in the left or right visual field. In addition, ERPs were also computed for trials where a positively or negatively cued nontarget appeared on the left or right side, and the target was located on the vertical midline (for positive and negative cue blocks only). ERPs were computed into 600 ms epochs (from 100 ms before to 500 ms after search display onset) relative to a 100 ms pre-stimulus baseline. Lateralized N2pc components were quantified on the basis of ERPs obtained at posterior electrode sites PO7 and PO8 contralateral and ipsilateral to the hemifield containing the target object. N2pc mean amplitudes were computed within a 200-280 ms post-stimulus time window. To assess whether some eye movements towards the location of the search targets remained present after artifact rejection, in particular during the critical N2pc time window, we compared bipolar HEOG waveforms obtained on trials where the target was located in the left versus right hemifield, separately for all three cue conditions. No systematic HEOG differences were present during the 200-280 ms time interval after search display onset in any of these comparisons (all t 's < 1.85 , p 's $> .09$).

To assess target N2pc onset latency differences between cue conditions, a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998) was employed, on the basis of difference waveforms computed by subtracting ipsilateral from contralateral ERPs. Grand averaged difference waves were computed for each condition, each excluding one participant from the original sample. Onset latencies were calculated for each of these subsamples, using a relative onset criterion of 50 % of the N2pc peak amplitude. For statistical tests of N2pc onset differences between conditions, F- and t-values were corrected according to the formulae described by Miller and colleagues (Miller et al., 1998; Ulrich & Miller, 2001). P_D components in response to lateral nontargets were measured in negative cue blocks on trials where the target was presented on the vertical midline. The onset latency of P_D components was found to be highly variable in previous studies, where the P_D emerged either before (Sawaki & Luck, 2010), during (Hickey et al., 2009) or after the N2pc (Sawaki, Geng, & Luck, 2012). Early and intermediate P_D latencies have been interpreted as evidence of efficient inhibition preventing attention being allocated to a distractor, whereas

a late-onset P_D may indicate suppressive processes that follow an initial distractor-induced capture of attention (e.g., attentional disengagement). Because we had no a priori predictions about P_D onset latency, we chose an intermediate interval (250-330 ms post-stimulus) to measure P_D mean amplitude.

Insert Figure 2 about here

Results

Behavioral data. Reaction time data from trials with correct responses that were within 3SDs of each individual's overall RT mean were used in this experiment, and in all subsequent experiments. Data were entered into a one-way ANOVA with the factor Cue Condition (Positive, Negative, Neutral). A significant effect was present ($F(2,22) = 17.14, p < .001, \eta_p^2 = .61$). RTs were fastest in blocks with positive cues ($M = 680$ ms), slowest in blocks with negative cues ($M = 758$ ms), and intermediate in neutral cue blocks ($M = 727$ ms). The RT benefit in positive as compared to neutral cue blocks was reliable ($t(11) = 3.59, p = .004, dz = 1.04$). Importantly, there was also a reliable RT cost in negative cue blocks relative to blocks with neutral cues ($t(11) = 2.70, p = .02, dz = .78$), as can be seen in Figure 2.¹ For error rates, there was also a significant effect of Cue Condition ($F(2,22) = 8.77, p < .005, \eta_p^2 = .44$). A positive cue benefit was present, with errors less frequent in positive cue blocks ($M = 15$ %) relative to blocks with neutral cues ($M = 20$ %; $t(11) = 4.18, p = .002, dz = 1.21$). There was no cost for error rates in negative versus neutral cue blocks (both $M = 20$ %; $t < 1$).

Insert Figure 3 about here

¹ Because cue displays contained a color cue on the left or right side, RTs may have been affected by the spatial correspondence between the position of this cue and the position of the subsequent target. To assess this, we ran an additional 2x2 ANOVA of RT data obtained on trials where the target object appeared on the left or right side, with the factors Cue Condition (Positive, Negative) and Spatial Correspondence (color cue and target on the same versus opposite sides). There was no significant main effect of Spatial Correspondence and no interaction with Cue Condition (both p 's $> .23$), indicating that the location of the color cue did not affect search performance.

N2pc components to target objects. Figure 3 shows grand average ERPs on trials where targets were presented laterally, measured at channels PO7/PO8 ipsilateral and contralateral to target items. Results are shown separately for the three cue conditions, together with the corresponding contralateral-ipsilateral difference waveforms are also shown. Target N2pc components were elicited in all three conditions, but appear to differ in their onset latency, with an early N2pc in positive cue blocks and an N2pc delay in blocks with negative cues. N2pc mean amplitudes obtained within a 200-280 ms post-stimulus interval were analysed with a 3x2 repeated-measures ANOVA with the factors Cue Condition (Positive, Negative, Neutral) and Laterality (Ipsilateral, Contralateral). A significant main effect of Laterality ($F(1,11) = 9.98, p = .009, \eta_p^2 = .48$), confirmed the reliable presence of N2pc components. There was marginally significant interaction with Cue Condition ($F(2,22) = 3.02, p = .069, \eta_p^2 = .22$), reflecting a trend for target N2pcs to be larger in positive relative to negative cue blocks (M diff = $-.90$ vs. $-.45 \mu\text{V}$), presumably due to the N2pc delay in negative cue blocks (see below). No reliable N2pc amplitude differences were observed between neutral and positive and between neutral and negative cue blocks. Comparisons of ipsilateral versus contralateral ERP amplitudes confirmed that significant N2pcs were present in positive and neutral cue blocks (t 's $> 2.68, p$'s $< .02, dz$'s $> .77$). In negative cue blocks, target N2pc was only marginally reliable during the 200-280 ms time window ($t(11) = 1.98, p = .07, dz = .57$), again due to its delayed onset towards the end of this pre-defined time window.

Target N2pc onset latencies were calculated on the basis of contralateral-ipsilateral waveforms, and submitted to jackknife-based analyses where onset was defined as 50% of the peak amplitude (up to 300 ms post-stimulus). The N2pc emerged earliest in the positive cue condition ($M = 205$ ms), followed by the neutral cue condition ($M = 230$ ms), and was most delayed in blocks with negative cues ($M = 252$ ms). A one-way ANOVA showed a significant effect of Cue Condition ($F_c(2,22) = 7.76, p = .003$), confirming that N2pc latencies differed between these three different types of blocks. Critically, there was reliable delay for N2pc onsets in blocks with negative as compared to neutral cues ($t_c(11) = 3.63, p = .004$). Although the corresponding benefit for N2pc onset latency for positive versus neutral cues was numerically similar to this N2pc latency cost with negative cues, it was only a non-significant trend ($t_c(11) = 1.70, p = .12$).

Insert Figure 4 about here

Lateralised ERP components to cued nontargets on trials with targets on the vertical midline. Figure 4 shows contralateral-ipsilateral difference waveforms obtained at PO7/8 in blocks with positive cues (black line) or negative cues (grey line) on trials where the nontarget item in the cued color was presented on the left or right and the target appeared on the vertical midline. Positively cued nontargets elicited a reliable N2pc component in the 200-280 ms post-stimulus time window (M diff = $-.73 \mu\text{V}$; $t(11) = 2.42$, $p = .03$, $d_z = .70$), indicating that these items attracted attention in spite of the fact that the target object was simultaneously present. In contrast, there was no evidence for the presence of a corresponding N2pc component, or alternatively, a P_D component, to cued nontargets during the same 200-280 ms time interval in negative cue blocks (M diff = $.27 \mu\text{V}$; $t < 1$). There was also no reliable lateralized effect during the later 250-330 ms time window in negative cue blocks (M diff = $.34 \mu\text{V}$; $t(11) = 1.11$, $p = .29$).²

Discussion of Experiment 1

Experiment 1 showed that positive templates for an upcoming target produced a clear benefit for search RTs relative to blocks with uninformative neutral cues, confirming the ability of positive cues to facilitate the guidance of attention during visual search. Target N2pc components also emerged earlier in blocks with positive as compared to neutral cues, although this was only a non-significant trend. The critical question was whether negative

² We also conducted exploratory analyses of N2pcs elicited by the color cues in the 200-280 ms period after cue onset to find evidence that participants allocated attention to positive and negative color cues, but not to neutral cues. A 3x2 repeated-measures ANOVA showed a significant Cue Condition x Laterality interaction ($F(2,22) = 4.15$, $p = .03$, $\eta^2 = .27$). For positive cues, a reliable N2pc was present (M diff = $-.46 \mu\text{V}$; $t(11) = 2.43$, $p = .03$, $d_z = .70$). For negative cues, a contralateral negativity was also present in the N2pc time range, but this difference was not reliable (M diff = $-.33 \mu\text{V}$; $t(11) = 1.42$, $p = .18$). For neutral cue displays, no lateralized negativity was elicited (M diff = $.01 \mu\text{V}$; $t < 1$).

cues would produce similar benefits for the guidance of search, or instead result in processing costs. The results of Experiment 1 provided clear converging behavioral and ERP evidence that negative cues interfered with the attentional selection of search targets. Relative to blocks with neutral cues, RTs were reliably slower in negative cue blocks, and target N2pc components were significantly delayed. The presence of these negative cue costs is in line with previous findings by Moher and Egeth (2012), but not with the results of Arita et al. (2012), who observed RT benefits following negative cues.

Moher and Egeth (2012) proposed that the costs produced by negative cues are a result of the fact that negatively cued items initially attract attention before they can be suppressed. This “search and destroy” hypothesis predicts that negatively cued nontargets should elicit N2pc components indicative of attentional capture. However, Experiment 1 found no evidence for this. Lateral nontarget items that matched the color of a negative cue did not trigger any lateralized activity during the N2pc time window on trials where target objects appeared on the vertical midline (and thus could not elicit an N2pc). The absence of an N2pc on these trials cannot be explained by the simultaneous presence of the target in the same search display, as positively cued lateral nontargets that were accompanied by a vertical target did trigger a clear N2pc (see Figure 4). Not only was there no support for the claim that attention is rapidly allocated to negatively cued items, Experiment 1 also provided no evidence that such items are subject to active inhibition, as indicated by a P_D component. No such component was present either during the N2pc time window or the later 250-350 ms post-stimulus interval.

The results of Experiment 1 are therefore difficult to reconcile with current ideas about the attentional processes triggered in response to negative cues. On the one hand, while the costs observed in negative cue blocks show that such cues interfere with the guidance of search towards target objects, there was no evidence for attentional capture by negatively cued nontargets (Moher & Egeth, 2012). On the other hand, the presence of clear negative cue costs is inconsistent with the suggestion that negative templates for rejection can facilitate search (Arita et al., 2012). However, it is important to note that different positive or negative cues were presented at the start of each trial in Experiment 1. Previous evidence suggests that any benefits of negative cues only emerge after repeated exposure to the same task-irrelevant feature across numerous successive trials (Vatterot &

Vercera, 2012; see also Cunningham & Egeth, 2016). The effects of this type of practice were investigated in Experiment 2, and in three subsequent experiments.

EXPERIMENT 2

Experiment 2 employed similar procedures as in Experiment 1, with two exceptions. First, only negative and neutral cue blocks were included. Second, and critically, each cue was now followed by three search displays. In negative cue blocks, cues again specified the color of two nontarget items, and these now remained constant in three successive search displays, while the target always appeared in a different randomly chosen color. In neutral cue blocks, the colors of the items in the three successive search displays never matched the color of the preceding cue. Repeating negatively cued color nontargets in three successive search displays might affect the activation of templates for rejection in two different ways. First, it could increase the incentive for participants to utilize negative search templates, as these could now be used to reduce effective set size in three separate search episodes. This could either produce behavioral and electrophysiological benefits for negative as compared to neutral cue blocks (e.g., Arita et al., 2012), or, alternatively, increase the probability of attentional capture by negatively cued nontarget items (Moher & Egeth, 2012), resulting in performance costs as well as in reliable N2pc components to these items. Second, repeated exposure to the same negatively cued color might facilitate learned distractor suppression (e.g., Vatterot & Vercera, 2012; Gaspelin et al., 2017; see also Cunningham & Egeth, 2016). If such learning processes operate rapidly, across three successive search episodes, RT costs for negative as compared to neutral cues should be observed for the first search display that immediately follows the cue, and these costs should be smaller or even change into benefits for the subsequent search displays. An analogous pattern of costs turning into benefits should also be observed for target N2pc components. In addition, P_D components indicative of active distractor suppression might emerge in Experiment 2 for negatively cued nontargets in the second and/or third search display within each run. To assess these predictions, lateralized ERP components were computed separately for search displays in the first, second, and third temporal position after the cue.

Method

Participants

Twelve participants were initially recruited to participate in Experiment 2. Of these, one participant was excluded and replaced with new participant data due to high eye blinks (> 60 %). Of the final sample (M age = 31 years, SD = 9; 8 male; 2 left-handed), all participants reported normal or corrected-to-normal vision.

Stimuli and Procedure

These were similar to Experiment 1, with the following exceptions. Participants now completed only negative and neutral cue blocks. In addition, each cue display was followed by three search displays. In negative cue blocks, the cue color signaled the color of two of the nontargets in all three of these displays (i.e., the target always appeared in a different color, which was randomly chosen for each of the three search displays). In neutral cue blocks, the two item colors for each search display were chosen randomly, but never matched the color of the cue. Cue and search displays were again presented for 100 ms, and the interval between two successive search displays was 2000 ms.

Following practice, participants completed 16 experimental blocks that included 72 search displays. Thus, each block contained 24 runs of a randomly chosen color cue followed by three search displays. Negative and neutral cue blocks were presented in an ABBA sequence, and the cue type for the first experimental block was counterbalanced across participants.

EEG Recording and Data Analysis

These were similar to Experiment 1. On average, 27% of all epochs were removed due to artifacts (ranging from 5% to 50% for individual participants). ERPs were computed separately for negative and neutral cue blocks, in response to search displays in position 1, 2, or 3, after the cue. Based on the results of Experiment 1, which found a substantial delay of target N2pcs in neutral and negative cue blocks (with onset latencies of 230 ms and 252 ms post-stimulus, respectively), a new time window of 250-330 ms after search display onset was utilized to quantify target N2pc mean amplitudes.

Results

Behavioral data: RT data from trials with correct responses were entered into a 3x2 ANOVA with the factors Search Display Position (First, Second, Third) and Cue Condition (Negative, Neutral). A main effect of Search Display Position ($F(2,22) = 6.04, p < .01, \eta_p^2 = .36$) was present. RTs were faster on the first trial immediately after a cue ($M = 680$ ms) compared to the second/third display ($M = 696$ and 695 ms; t 's $> 2.44, p$'s $< .04, dz$'s $> .70$), which did not reliably differ ($t < 1$). Importantly, there was also a significant main effect of Cue Condition ($F(1,11) = 23.79, p < .001, \eta_p^2 = .68$). As in Experiment 1, there was a clear RT cost for negative cues as compared to blocks with neutral cues ($M = 702$ vs. 679 ms). However, the Search Display Position x Cue Condition interaction was not significant ($F(2,22) = 2.45, p = .11, \eta_p^2 = .18$). There was no evidence that negative cue costs decreased or reversed across successive search displays; for this reason, Figure 2 presents mean RT data collapsed across search display position. If anything, these costs increased: for the first search display following a cue, they were only marginally significant (M diff = 14 ms; $t(11) = 2.02, p = .069, dz = .58$). For the second and third search display, they were larger and reliable (M diff = 26 and 31 ms; t 's $> 3.58, p$'s $< .01, dz$'s > 1.03). For error rates, a main effect of Search Display Position was present ($F(2,22) = 3.64, p < .05, \eta_p^2 = .25$), due to a small but systematic increase in errors for the third and final search display within a run ($M = 17\%$) relative the first and second display (both $M = 16\%$; t 's $> 2.51, p$'s $< .03, dz$'s $> .72$). There was no significant main effect of Cue Condition and no two-way interaction (F 's < 1).

Insert Figure 5 about here

N2pc components to target objects: Figure 5 shows N2pc difference waveforms obtained on trials where targets were presented laterally by subtracting ERPs measured at PO7/PO8 ipsilateral to the target from contralateral ERPs, separately for the first, second, and third search display after a cue, in blocks with negative and neutral cues. As in Experiment 1, target N2pcs were delayed with negative cues, and this delay did not seem to be modulated by the temporal position of a search display. An N2pc mean amplitude analysis with the factors Search Display Position (First, Second, Third), Cue Condition

(Negative, Neutral), and Laterality (Ipsilateral, Contralateral) obtained a significant main effect of Laterality ($F(1,11) = 25.64, p < .001, \eta_p^2 = .70$) confirming the presence of reliable target N2pc components. Laterality did not significantly interact with Search Display Position ($F(2,22) = 2.39, p = .12$), Cue Condition ($F < 1$), and there was no significant three-way interaction ($F < 1$). The jackknife-based analysis of N2pc onset latencies found a significant main effect of Cue Condition ($F_c(1,11) = 10.86, p < .01$). Analogous to Experiment 1, there was a general N2pc onset delay in blocks with negative cues relative to neutral cue blocks ($M = 274$ vs. 264 ms). There was also a main effect of Search Display Position ($F_c(2,22) = 3.59, p < .05$), as target N2pcs emerged earlier for the final as compared to the second search display within each run ($M = 259$ vs. 277 ms; $t_c(11) = 3.20, p < .01$). Finally, a significant Search Display Position x Cue Condition interaction was present ($F_c(2,22) = 3.50, p < .05$). For the first search display after a cue, target N2pc components were reliably delayed in negative as compared to neutral cue blocks ($M = 282$ vs. 258 ms; $t_c(11) = 2.84, p < .02$), confirming the results of Experiment 1. For the second display within a run, this N2pc onset latency cost disappeared, and was numerically reversed ($M = 274$ vs. 280 ms; $t_c < 1$). For the third and final search display, there was again a numerical trend for a negative cue cost on N2pc onset latency ($M = 267$ vs. 253 ms), but this difference was not significant ($t_c(11) = 1.86, p = .089$).

Lateralised ERP components to negatively cued nontargets in displays with targets on the vertical midline: Figure 6 shows contralateral-ipsilateral difference waveforms obtained at PO7/8 in negative cue blocks in search displays where a negatively cued nontarget item was on the left or right side and the target appeared on the vertical midline, separately for search displays in position 1, 2, or 3 after the cue. As in Experiment 1, there was no evidence for an early N2pc component to these items. In fact, during the 200-280 ms post-stimulus interval that was used in Experiment 1, a main effect of Laterality ($F(1,11) = 5.77, p = .04, \eta_p^2 = .34$) was present, but reflected a small but reliable contralateral *positivity* (M diff = $.27 \mu V$), presumably indicating the early phase of the P_D component. There was no interaction between Laterality and Search Display Position ($F < 1$) in this time window. The presence of P_D components was confirmed in an analysis of mean amplitudes in the 250-330 ms post-stimulus interval. Again, a significant main effect of Laterality ($F(1,11) = 8.46, p = .014, \eta_p^2 = .44$) was present in the absence of an interaction between Laterality and Search Display

Position ($F < 1$), indicating that this effect did not differ across the three successive search displays after a negative cue.

Insert Figure 6 about here

Discussion of Experiment 2

Experiment 2 demonstrated that negative cues incur costs for the guidance of attention even when the information about task-irrelevant nontargets provided by these cues remains valid across three successive search episodes. Confirming the results of Experiment 1, RTs were slower and target N2pc components emerged later in blocks with negative as compared to neutral cues. The negative cue costs on RTs did not diminish in size for the second and third search display within each run; if anything, they became larger for these displays. There was also no clear evidence that the costs observed for N2pc onset latencies in negative versus neutral cue blocks were affected by the temporal position of a search display, although these costs were numerically largest for the display that immediately followed the cue. The variability of these costs for N2pc onset latencies across the three display positions may reflect limitations in individual signal-to-noise ratios of N2pcs quantified separately for these positions, as interindividual variability can affect the quality of latency estimates obtained with jackknife-based procedures. Overall, the RT and N2pc results obtained in Experiment 2 showed that three repetitions of the same cued nontarget feature are not sufficient to eliminate the adverse effects of negative cues on the guidance of attention in visual search.

Despite the presence of clear behavioral and electrophysiological costs on search target selection, there was still no evidence for any rapid attentional capture by negatively cued nontargets (as suggested by Moher & Egeth, 2012). As in Experiment 1, these items did not elicit any N2pc components in displays where they were accompanied by vertical targets. However, and in contrast to Experiment 1, reliable P_D components were observed in Experiment 2 in response to negatively cued lateral nontarget objects (Figure 6). If this component reflects the suppression of an “attend-to-me-signal” (e.g., Gaspelin & Luck,

2018b), its presence in response to these objects in Experiment 2 suggest that they were sufficiently salient to be registered by pre-attentive processes. This could indicate that a template for rejection was indeed activated to some degree, prioritizing the perceptual processing of template-matching objects, which then was actively inhibited. The fact that no P_D components were found in Experiment 1 could indicate that the presence of three successive search displays with the same negatively cued color nontargets in Experiment 2 made it more likely that participants activated a template for rejection on at least some trials.

This hypothesis may seem difficult to reconcile with the fact that negative cues actually produced performance costs in Experiment 2, indicating that it would have been more adaptive for participants not to employ such negative templates at all. However, it is possible that such templates will eventually facilitate search performance with extensive practice. Such a shift from initial performance costs for negative cues to subsequent have previously been found both for salient singleton distractors (Vatterrot & Vecera, 2012) and also for cued non-salient distractors (Cunningham & Egeth, 2016). In Experiments 3 and 4, we tested with behavioral measures whether an analogous reversal can also be observed with the cueing and search procedures used in the present study. In Experiment 5, we employed ERPs to find out whether the emergence of behavioral benefits for negative cues is associated with the inhibition of negatively cued nontarget objects.

EXPERIMENTS 3 AND 4

Experiments 1 and 2 demonstrated that negative cues that signal a task-irrelevant nontarget color in an upcoming search display incur performance costs, and that these costs remain present when the same negatively cued color appears in three successive search displays (Experiment 2). In Experiments 3 and 4, we investigated whether and when such costs turn into performance benefits once negative cues remain valid for longer periods of time. The emergence of such benefits could indicate that following extended practice, templates for rejection are activated and can be used to guide attention away from negatively cued nontargets. Procedures were similar to Experiment 2, except that negative or neutral color cues were now only shown once, at the start of each block, and were followed by 72 search displays. In Experiment 3, a different color cue was presented in each block. To assess the time course of negative cue costs with repeated exposure to the same

cued nontargets across multiple search displays, performance in negative and neutral cue blocks was compared separately for trial tertiles within each block (i.e. trials 1-24, 25-48, and 49-72). The presence of constant negative cue costs for three successive trials observed in Experiment 2 indicates that such costs do not disappear rapidly with practice. They may thus still be reliably present for the first 24 trials within each block in Experiment 3. The critical question was whether these costs become smaller for later trials, or might even convert into negative cue benefits towards the end of each block.

Experiment 4 used analogous procedures, except that the same color cue was now used throughout the experiment. Eight negative cue blocks and eight neutral cue blocks were run. Thus, there were 576 search displays where the same negatively cued pair of color nontargets was present. Performance in negative and neutral cue blocks was compared for each ordinal block position (1-8) within the experiment. The question was again whether and when any negative cue benefits would emerge. Previous results by Cunningham and Egeth (2015) suggest that it may take several hundred trials of practice with the same negative color cue before reliable benefits emerge. However, this study also found that fewer trials might be needed when such cues specify the color of multiple nontargets in the same search display. If that was correct, negative cue benefits should be found in Experiment 4 only for later blocks, but not for earlier blocks.

Method

Participants

Twelve participants took part in Experiment 3 (M age = 30 years, SD = 7; 6 male, 1 left-handed and one declared ambidextrous). Twelve participants were also tested in Experiment 4 (M age = 29 years, SD = 8; 5 male; 1 left-handed). All reported normal or corrected-to-normal vision.

Stimuli and Procedure

These were similar to Experiment 2, with the following exceptions. In both experiments, the cue display was shown only once at the start of each block. Following the cue, each block included 72 trials where search displays were shown, at intervals of 2000 ms. Each experiment contained a total of 16 blocks. In negative cue blocks, two nontarget items in the search displays always appeared in the cued color, while the target and another

nontarget item appeared in a different color that was randomly chosen for each search display. In neutral cue blocks, the cued color never appeared in any search display. The main difference between Experiments 3 and 4 was that cue colors either changed between blocks or remained constant throughout. In Experiment 3, a different randomly selected negative or neutral color cue was presented at the start of each block. Blocks with negative or neutral cues were rotated, following an ABBA or BAAB order, counterbalanced across participants. In Experiment 4, only a single cue color was used, both for negative and neutral cue blocks. Here, participants completed four successive blocks for one cue condition (negative or neutral). The order of cue conditions was rotated every four blocks, in a counterbalanced ABBA/BAAB order. This was done to ensure that participants would have extended practice with negative cues across multiple blocks, while at the same time avoiding asymmetric cue-unspecific practice effects that would have been present if participants had completed all eight neutral cue blocks prior to the eight negative cue blocks, or vice versa.

Given the blocked cue design in Experiments 3 and 4, participants were likely to notice almost immediately that knowledge about which color would not appear in any search display (in neutral cue blocks) was not helpful in guiding search. For this reason, participants were still encouraged to use the negative color cue as it was “helpful” (as in the previous experiments), but were told that the neutral cue was “not very helpful” as they would still have to search all four locations in search displays to locate the target.

Data Analysis

For Experiment 3, performance differences between negative and neutral cue blocks were assessed for tertiles of trials within each block (i.e., the first 24 trials in each block that followed the presentation of a new cue color, trials 25-48, and trials 49-72). As the sequence of blocked cue conditions followed an ABBA order in Experiment 3, blocks 1 and 2 for one cue condition will correspond to the 1st and 5th experimental block, and to the 3rd and 4th experimental block for the other cue condition (and analogously for subsequent blocks). As the order of cue conditions was counterbalanced between participants, this should not result in any asymmetric practice effects between cue conditions. For Experiment 4, performance was measured separately for each pair of two successive blocks of the same type (i.e., negative/neutral cue blocks 1-2, 3-4, 5-6, 7-8), and the presence of negative cue

costs or benefits was assessed for each of these four ordinal block positions (i.e., negative blocks 1/2 versus neutral blocks 1/2, up to negative blocks 7/8 versus neutral blocks 7/8).

Results

Experiment 3. RT data measured in trials with correct responses were entered into a 3x2 repeated-measures ANOVA with the factors Block Tertile (First, Second, Third) and Cue Condition (Negative, Neutral). There was no main effect of Block Tertile ($F < 1$), but a significant main effect of Cue Condition was present ($F(1,11) = 9.94, p = .009, \eta_p^2 = .48$). Analogous to Experiments 1 and 2, there was a general RT cost for negative as compared to neutral cues ($M = 706$ vs. 689 ms). This was qualified, however, by a significant Block Tertile x Cue Condition interaction ($F(2,22) = 4.69, p = .02, \eta_p^2 = .30$), as illustrated in Figure 2. To assess this, RT costs for negative as compared to neutral cue blocks were calculated for each tertile of trials. A clear cost of 32 ms was evident over the first 24 trials of a block ($M = 718$ vs. 686 ms; $t(11) = 5.16, p < .001, dz = 1.49$). However, this difference reduced to a non-significant 14 ms cost in the second tertile ($M = 704$ vs. 690 ms; $t(11) = 1.36, p = .20$) and to 3 ms in the final tertile ($M = 695$ vs. 692 ms; $t < 1$).

A matching analysis on error rates showed no main effect of Block Tertile ($F < 1$) but a significant main effect of Cue Condition ($F(1,11) = 23.03, p = .001, \eta_p^2 = .68$), with fewer errors in negative as compared to neutral cue blocks ($M = 13$ vs. 16 %). There was no Block Tertile x Cue Condition interaction for error rates ($F < 1$).

Experiment 4. Figure 2 (lower panel) illustrates mean RTs for blocks 1/2, 3/4, 5/6, and 7/8, separately for neutral and negative cue blocks. RT benefits for negative cue blocks are represented by positive and costs by negative values. Results indicate that there were neither negative cue costs nor benefits for the first four blocks, benefits emerged in later blocks, and were largest in the final two blocks. Paired t-tests revealed a significant negative cue benefit for blocks 7/8 ($M = 627$ ms and 597 ms in neutral and negative cue blocks, respectively, M diff= 30 ms, $t(11) = 5.64, p < .001$). For all earlier block pairs, RTs did not differ reliably between neutral and negative blocks (all t 's $< 1.24, p$'s $> .24$).

An analogous comparison of error rates produced similar results. Paired t-tests showed a significant negative cue benefit for blocks 7/8 ($M = 11$ % and 7 % in neutral and

negative cue blocks, respectively, M diff = 4 %; $t(11) = 2.78$, $p = .02$, $d_z = .80$), but no reliable differences in other blocks (all t 's < 1.79, p 's > .10).

Discussion of Experiments 3 and 4

Experiments 3 and 4 assessed whether and when repeated exposure to the same negatively cued nontargets across multiple successive trials within the same block, or across several blocks, would result in a reversal of negative cue costs for search performance into benefits. In Experiment 3, RT costs for negative cues were observed for the first 24 trials within a block, and these costs were at least as large as the costs observed in Experiments 1 and 2. However, costs decreased in the course of each block, and were virtually absent for the final 24 trials. One possibility is that participants may have simply abandoned any attempt to use the information provided by negative cues on these trials, and then ignored these cues in the same way as cues in neutral blocks. Alternatively, the gradual attenuation of negative cue costs during each block in Experiment 3 might reflect the initial effects of slow learned suppression mechanisms that would have eventually resulted in negative cue benefits for search RTs if more time had been available (e.g., Cunningham & Egeth, 2016). The observation that error rates were generally smaller in negative as compared to neutral cue blocks in Experiment 3 is in line with this possibility.

Critically, in Experiment 4, where the same negative cue was valid in all blocks, an overall negative cue benefit was finally observed for both RT and error rates. This result, which contrasts with the presence of negative cue costs in all three previous experiments, demonstrates that knowledge about nontarget features can facilitate search performance, but that extended practice is required for such effects to emerge. The fact that neither costs nor reliable benefits were present in the first two blocks of Experiment 4 is consistent with the observation of Experiment 3 that these costs were only present for the first 24 trials within each block. If the absence of such costs on later trials had been the result of participants abandoning the information provided by negative cues at some point during the first block after a new cue was introduced, these cues should not have resulted in benefits in later blocks in Experiment 4. Thus, the presence of these benefits shows that the repeated presentation of the same color-defined nontargets across many successive trials did eventually facilitate the guidance of attention towards search targets.

These findings, which are consistent with previous observations by Cunningham and Egeth (2015), raise the question which mechanisms are responsible for the practice-dependent negative cue benefits for search performance revealed in Experiment 4. One possibility is that these benefits are the result of the slow acquisition of search templates for rejection. Once established, such templates might actively suppress the attentional processing of negatively cued nontargets, thereby facilitating the guidance of attention towards targets. Alternatively, negative cue benefits may not be linked to such learned active suppression mechanisms, but instead be the result of passive habituation to nontarget features that are consistently repeated across multiple blocks. In our final experiment, we employed ERP markers of distractor suppression to distinguish between these two accounts.

EXPERIMENT 5

If the negative cue benefits observed in Experiment 4 after extended practice were produced by the active suppression of nontargets that matched a learned template for rejection, these suppression mechanisms might be revealed by ERP markers. In particular, P_D components elicited by distractors in visual search displays have previously been associated with such inhibition mechanisms (Gaspelin & Luck, 2018b). In the current Experiment 2, such P_D components were elicited by negatively cued nontargets under conditions where negative cues were followed by only three search displays, and where these cues produced performance costs rather than benefits. This may suggest that any suppression reflected by this component does not require extensive practice, and does not result in any search benefits. However, it is possible that the P_D components found in Experiment 2 only reflect the earliest phase in the acquisition of templates for rejection, where the activation of such templates for rejection and the subsequent inhibition of template-matching nontargets requires active top-down executive control. During this early phase of learning, distractor suppression might be slow and actually interfere with the parallel guidance of attention towards search targets. Extended exposure to the same negatively cued nontargets across multiple trials may make learned suppression more effective, resulting in benefits rather than costs for search performance, and in earlier and possibly also larger inhibition-related P_D components.

To test this prediction, Experiment 5 included twelve successive negative cue blocks, to maximize the chances of observing the development of learned suppression mediated by templates for rejection, based on ERP markers obtained during task performance. As in Experiments 1 and 2, P_D components to lateral negatively cued distractors were measured on trials where targets appeared above or below fixation in the same search display, and thus could not elicit any lateralized ERPs. To assess whether and how P_D components reflect increasing task practice, they were computed separately for the first four blocks, blocks 5-8, and the final blocks 9-12. If sustained exposure to the same nontargets facilitates learned suppression, P_D components should emerge earlier and become larger in the course of the experiment. In addition, any facilitation of target selection by learned distractor suppression might also result in earlier and/or larger target N2pc components for later as compared to earlier blocks. Therefore target N2pcs were also measured separately for blocks 1-4, 5-8, and 9-12. Alternatively, if the negative cue benefits observed in Experiment 4 reflect passive habituation after multiple presentations of the same color nontargets, without any involvement of template-guided suppression processes, no such P_D differences should be observed in Experiment 5. In fact, negatively cued items may not be actively inhibited at all after extended practice, in which case P_D components should be entirely absent.

Because all negative cue blocks were run successively in Experiment 1, it was not possible to directly quantify behavioral negative cue benefits by comparing performance in interleaved negative and neutral cue blocks, as in Experiments 3 and 4. To verify that such benefits were indeed present, four neutral cue blocks were included at the end of the experiment, after participants had completed all negative cue blocks.

Method

Participants

Twelve participants were initially recruited to take part in Experiment 5. One participant was excluded and replaced with new participant data due to a high percentage of trials excluded due to excessive eye blinks (> 60 % of all trials). Of the final sample (M age = 28 years, SD = 9; 6 male; 3 left-handed), all reported normal or corrected-to-normal vision.

Stimuli and Procedures

These were identical to Experiment 4 with the following exceptions. Participants completed 16 experimental blocks of 72 trials each. All started with 12 successive negative cue blocks, followed by 4 neutral cue blocks.

EEG Data Recording and Analysis

These were analogous to Experiments 1 and 2. Artifact rejection led to an average removal of 22% of all epochs (ranging from 12% to 37% for individual participants). To measure P_D components to negatively cued nontargets, ERPs obtained in negative cue blocks in response to search displays that contained a negatively cued nontarget on the left and right side and a target on the vertical midline were computed, separately for blocks 1-4, 5-8, and 9-12. As in Experiment 2, P_D mean amplitudes were quantified within a 250-330 ms post-stimulus time window. In addition, N2pc components to displays with lateral search targets were also measured separately for these three negative cue block tertiles. N2pc mean amplitudes were also measured within a 250-330 ms time window, and N2pc onset latencies for each block tertile were computed and compared, using the same jackknife-based methods as in Experiments 1 and 2.

Results

Insert Figure 7 about here

Behavioral data: Figure 7 shows mean RTs across the three block tertiles (1-4, 5-8, 9-12) in negative cue blocks. For comparison, mean RT in neutral cue blocks that followed the negative cue blocks is also shown. Note that since neutral cue blocks were always run last, performance in these blocks should profit most from cue-unrelated generic practice effects. As expected, RTs in negative cue blocks became faster in the course of the experiment (main effect of Block Tertile: $F(2,22) = 9.31$, $p = .001$, $\eta_p^2 = .46$). Differences between RTs in the three negative cue block tertiles and RTs in neutral cue blocks ($M = 642$ ms) were assessed with a series of paired-sample t-tests. Relative to neutral cue blocks, RTs were slower in the first tertile of negative cue blocks ($M = 679$ ms; M diff = 37 ms; $t(11) = 2.52$, $p =$

.03, $d_z = .73$) and showed no difference in the second tertile ($M = 642$ ms; M diff = 0 ms; $t < 1$). Importantly, RTs in negative cue blocks 9-12 were reliably faster than RTs in the subsequent four neutral cue blocks ($M = 623$ ms; M diff = 19 ms; $t(11) = 3.06$, $p = .01$, $d_z = .88$), demonstrating a negative cue benefit. A matching analysis of error rates did not show a reliable reduction with extended practice in negative cue blocks (main effect of Block Tertile: $F(2,22) = 1.26$, $p = .30$). Error rates in neutral cue blocks ($M = 11\%$) did not differ reliably from error rates in the first and second tertile of negative cue blocks ($M = 11$ and 10% , versus 12% ; t 's < 1.46 , p 's $> .17$). However, error rate was lower in the third tertile of negative cue blocks relative to neutral cue blocks ($M = 9\%$; M diff = 3% ; $t(11) = 3.08$, $p = .01$, $d_z = .89$).

Insert Figure 8 about here

Lateralized ERPs to search targets and negatively cued nontargets: Figure 8 shows grand average contralateral-ipsilateral difference waveforms obtained in the first, second, and third tertile of negative cue blocks for negatively cued lateral nontargets on trials with targets on the vertical midline (left panel) and for lateral search targets (right panel). Targets elicited clear N2pc components with very similar amplitudes and onset latencies in all three block tertiles. In contrast, negatively cued lateral nontargets did not elicit a very clear contralateral positivity. There was no indication that P_D components in response to these objects emerged earlier or increased in size for later as compared to earlier negative cue blocks. Mean amplitudes of P_D components conducted within a 250-330 ms post-stimulus onset were submitted to a 3x2 repeated-measures ANOVA with the factors Block Tertile (blocks 1-4,5-8, 9-12) and Laterality. The evidence for the presence of P_D components was no more than a trend, as the main effect of Laterality failed to reach significance ($F(1,11) = 3.69$, $p = .08$, $\eta_p^2 = .25$). There was also no interaction between Laterality and Block Tertile ($F < 1$), confirming that P_D components did not increase in size with prolonged exposure to negatively cued nontargets. Planned follow-up paired t-tests comparing contralateral and ipsilateral ERPs found no overall reliable P_D components for any of the three negative cue block tertiles (t 's < 1.74 , p 's $> .10$).

For target N2pc components (Figure 8, right panel), an analogous ANOVA of mean amplitudes showed a significant main effect of Laterality ($F(1,11) = 41.12, p < .001, \eta_p^2 = .79$), demonstrating the presence of reliable N2pc components. There was no interaction between Laterality and Block Tertile ($F < 1$), indicating that target N2pc amplitudes did not change as practice with negative cue blocks increased. A jackknife-based N2pc onset latency analysis also showed no significant main effect of Block Tertile ($F_c < 1$), confirming that the onset of target N2pcs remained constant across all negative cue blocks. An additional comparison of target N2pc components between negative cue blocks 9-12 and the subsequent four neutral cue blocks also found no reliable differences for either N2pc amplitudes ($t < 1$) or onset latencies ($t_c < 1$).

Discussion of Experiment 5

Experiment 5 confirmed the finding from Experiment 4 that extended exposure to the same negatively cued nontargets can produce performance benefits relative to blocks where the color of these nontargets is not predictable. RTs were faster and errors less frequent in the final four negative cue blocks than in the following four neutral cue blocks. Because neutral cue blocks were delivered at the end of the experiment, generic practice effects should have been maximal in these blocks. Thus, the observation that performance was actually better in the preceding blocks with negative cues provides clear evidence that these cues can produce behavioral benefits.

If the emergence of performance benefits in negative cue blocks was due to learned active suppression mechanisms that are mediated by templates for rejection, this should have been reflected by reliable P_D components to negatively cued nontargets, and in particular by earlier and larger P_D components in the final four as compared to the first four negative cue blocks. However, no such evidence was found. P_D components observed on trials with lateral negatively cued nontargets were generally very small. They were not statistically reliable within any block tertile, and also not across all negative cue blocks. Furthermore, there was no evidence that these components were larger or emerged earlier in the final four blocks. Even though behavioral negative cue benefits were found in these blocks relative to the subsequent neutral cue blocks, this was not reflected by corresponding benefits for target N2pc onset latencies, which also did not differ between negative cue block tertiles. Overall, Experiment 5 revealed no clear electrophysiological

correlates of negative cue benefits that emerge with extended practice. The implications of this result will be further discussed below.

GENERAL DISCUSSION

The question as to whether preparatory representations of known distractor features (“templates for rejection”) are involved in the guidance of visual search remains unresolved (e.g., Arita et al., 2012; Moher & Egeth, 2012). In the present study, we investigated this issue by combining performance measures with ERP markers of attentional target selection and nontarget suppression. Experiments 1 and 2 demonstrated that negative cues providing information about the color of nontargets in upcoming search displays produce performance costs rather than benefits when compared to non-informative neutral cues. These costs were also evident in delays of target N2pc components in trials with negative cues, indicating that these cues impair the speed of attentional target selection. These results confirm previous observations by Moher and Egeth (2012), but are clearly inconsistent with Arita et al. (2012), who observed benefits immediately after a new negative cue was presented (see Beck & Hollingworth, 2015, for an alternative location-based selection explanation of these findings).

Moher and Egeth (2012) suggested that the performance costs observed following negative cues are produced because cued items are initially attended before they can be suppressed (“search and destroy”). We found no ERP evidence to support this hypothesis. If negatively cued lateral nontargets had attracted attention, they should have elicited N2pc components in Experiments 1 and 2 when they were accompanied by search targets on the vertical midline. Such N2pcs were conspicuously absent in both experiments. In contrast, positively cued lateral nontargets triggered significant N2pc components in Experiment 1, demonstrating that N2pcs associated with allocating attention to nontargets can be reliably measured even when a vertical target is present in the same search display. Also, previous ERP studies of attentional capture have found close links between the presence versus absence of behavioral attentional capture effects and the presence versus absence of N2pc components (e.g., Eimer & Kiss, 2008; Lien, Ruthruff, & Cornett, 2010). Thus, the absence of N2pcs to negatively cued nontargets in Experiments 1 and 2 suggests that the neural and

thus presumably also the cognitive processes that are triggered in response to these items differ from those that are typically elicited during attentional capture.

If negative cue costs are not the result of attentional capture by negatively cued items, which other processes might be responsible for these costs? Another possibility is that they arise because these items are pre-attentively registered and then rapidly suppressed. Such a “register and destroy” scenario is not dissimilar to the “search and destroy” hypothesis proposed by Moher and Egeth (2012), except that it rejects the idea that negatively cued items are actively attended. Instead, it assumes that costs arise due to an interference between the detection and suppression of negatively cued items and the simultaneous guidance of attention towards targets. Some evidence for active suppression was indeed found in Experiment 2, where negatively cued nontargets elicited reliable P_D components that are usually interpreted as markers of distractor inhibition (e.g., Gaspelin & Luck, 2018b). It should be noted that no P_D was observed in Experiment 1, in spite of the fact that negative cues elicited reliable performance costs, indicating that the suppression of negatively cued items is not a sufficient condition for such costs to be present. It is possible that these costs arise whenever these items that match the cued template for rejection are registered pre-attentively and are not fully suppressed. In order for suppression to operate effectively, negatively cued items may need to be presented repeatedly across successive trials. In this case, the P_D components observed in Experiment 2 where three successive search displays were presented after each negative cue could reflect an early phase of this learned suppression process, where some inhibition was applied to negatively cued nontargets, but not enough to prevent performance costs relative to neutral cue trials.

This learned suppression account is consistent with previous observations that negative cue costs eventually turn into benefits, but only after extended consistent practice (e.g., Cunningham & Egeth, 2016). In Experiments 3 to 5, we demonstrated such a practice-induced transition from costs to benefits with the specific search procedures used in the present study. In Experiment 3, where the same color-defined nontargets appeared in all 72 search displays within a block, negative cue costs were reliably present for the first 24 trials, and dissipated afterwards. Experiments 4 and 5 demonstrated that performance benefits for negative cues took much longer to emerge, and that such benefits were only reliably present after exposure to the same negatively cued nontargets for several hundreds of trials. If this reversal of negative cue costs into benefits reflects the development of more

effective nontarget inhibition with increased exposure, this should have been reflected by systematic modulations of inhibition-related P_D components. This component should emerge earlier and be larger once learned suppression processes were fully activated as a result of extended practice. However, the results of Experiment 5 did not support these predictions. P_D components to negatively cued nontargets were very small and not statistically reliable, and showed no onset latency or amplitude modulations across twelve successive negative cue blocks.

The absence of any electrophysiological support for learned suppression as the source of negative cue benefits in Experiment 5 cannot be regarded as conclusive evidence against this hypothesis, as it remains possible that this type of suppression is simply not reflected by P_D components. For example, it could be argued that these components are only elicited during the inhibition of “attend-to-me” signals triggered by physically salient but task-irrelevant distractors such as feature singletons (Gaspelin & Luck, 2018b). If this was the case, no reliable P_D may have been found in Experiment 5 because the negatively cued items were not sufficiently salient. However, a recent study by Wang, van Driel, Ort, and Theeuwes (2019) found a reliable P_D to non-salient distractor items when these items appeared at a location where a singleton distractor was expected, demonstrating that this component is not exclusively triggered in response to bottom-up salience signals in visual search displays.

In this case, the absence of evidence for learned suppression controlled by templates for rejection in Experiment 5 suggests that a different type of mechanism may be responsible for the emergence of negative cue benefits after extended practice. One possibility is that these effects are the result of passive habituation processes. Inspired by early work by Sokolov (1963), numerous studies have demonstrated strong attenuations of behavioral and neural responsiveness resulting from repeated presentation of the same stimulus (e.g., Bell, Röer, Dentale, & Buchner, 2012). Importantly, habituation may also play a role for distractor inhibition in visual search (see Chelazzi et al., 2019, for review). For example, Turatto and Pascucci (2016) have demonstrated that attentional capture by salient distractors in visual search displays is eliminated when the same distractor is repeated for extended periods. Notably, this effect can also be produced by passively viewing search display sequences (Turatto, Bonetti, Pascucci, & Chelazzi, 2018; see also Won & Geng, in press, for similar observations), strongly suggesting that it reflects passive habituation

rather than a strategic acquisition of task-specific templates for rejection. Given these findings, it is plausible to assume that the negative cue benefits that emerged with extensive practice in the present study, as well as similar benefits observed previously (Cunningham & Egeth, 2016), are the result of such habituation mechanisms. Repeated exposure to the same color-defined nontargets in successive negative cue blocks gradually produces an attenuation of visual responses to these items, which reduces their ability to compete with the target for attentional processing, thus eventually resulting in performance benefits relative to neutral cue blocks where no such habituation processes are present. Importantly, since habituation is essentially an automatic stimulus-driven process, this account implies that negative cue benefits are unrelated to active templates for suppression that facilitate learned distractor suppression.

Overall, the results of the current study suggest that the initial costs and subsequent benefits of negatively cueing nontarget features in visual search reflect two entirely different mechanisms. Performance costs emerge initially for a number of trials after a new nontarget is specified and a corresponding template for rejection is activated. Objects matching this template are pre-attentively registered and subsequently inhibited (as reflected by P_D components). Even though they do not attract focal attention (as reflected by the absence of an N2pc), this “register and destroy” process interferes with the parallel guidance of attention towards search targets. When the same nontarget objects are repeated for longer periods (e.g., on more than 20 or 30 successive trials; Experiment 3), habituation effects begin to emerge, which reduce the likelihood that these objects will be pre-attentively detected and inhibited, thus eliminating negative cue costs. After exposure to these objects for several hundreds of trials, habituation reduces activation levels to below baseline (i.e., the activation of nontarget objects in neutral cue blocks). As a result, they can be easily ignored, no longer compete with search targets for attentional selection on the majority of trials, and negative cue benefits emerge.

If negative cue costs and benefits are produced by different processes, this could also account for the observation that RT and N2pc onset latency measures were broadly consistent in Experiments 1 and 2, where both showed reliable negative cue costs, but not in Experiment 5, where negative cue benefits for RT in the final block tertile were not accompanied by corresponding target N2pc latency benefits. This could suggest that interference associated with the short-term activation of templates for rejection delays the

rapid allocation of attention to search targets, as reflected by the N2pc, while longer-term habituation may primarily affect later stages of attentional selectivity, such as the competition between targets and negatively cued nontargets for access to visual working memory. Although consistent with the pattern of results observed in the present study, this possibility remains speculative at present, and will need to be tested in future experiments with appropriate behavioral and electrophysiological markers.

According to the account proposed here, the activation of templates for rejection is associated with performance costs that are only present for a limited number of trials. This raises the additional question whether such templates remain active after such costs have dissipated, and even at the later time when performance benefits are observed. While the current results cannot provide a conclusive answer, the fact that some evidence for the presence of residual P_D components was found in Experiment 5 even after the same negatively cued nontargets had been encountered in multiple blocks and performance benefits emerged could be important. It suggests that template-guided “register and destroy” processes may have been activated on a small number of trials even after extensive practice.

In summary, the results of the current study challenge suggestions that attentional templates for the rejection of known nontarget objects can be effectively employed in the guidance of visual search by directing attention away from these objects and expediting the selection of targets (e.g., Arita et al., 2012). Instead, we found that such templates produce performance costs and delay the allocation of attention to search targets. Even though performance benefits do emerge after extensive practice with constant nontargets, these benefits do not appear to be produced by template-guided learned suppression mechanisms, but may instead reflect passive habituation processes.

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Figure captions

Figure 1: Example experimental trials (not to scale) in Experiment 1. On each trial, a cue display was followed by a search display containing four outline square in two different colors with a small gap in one of their sides. The search target contained a gap at the top or bottom. In positive cue blocks (panel A; target on the left), cues indicated the color of the upcoming target object. In the negative cue condition (panel B; target on the right), the cue specified the color of two nontarget objects, and the target would always appear in a different color. In the neutral cue condition (panel C; target at the top), the cued color never appeared in the upcoming search display.

Figure 2: Mean RT data in Experiments 1-3 (upper panel) and Experiment 4 (lower panel). Experiment 1 contained positive, negative, and neutral cue conditions, whereas Experiments 2-4 contained negative and neutral conditions only. In Experiment 3, data is split by block tertile. Data in Experiment 4 is split by blocks 1/2, 3/4, 5/6, and 7/8. Error bars denote ± 1 SE.

Figure 3: (Top panels) Grand average ERPs obtained in Experiment 1 in the 500 ms interval after the presentation of a search display, at posterior electrode sites PO7/PO8 contralateral and ipsilateral to the hemifield containing a target object. ERPs are shown separately for each cue condition. (Bottom panel) The corresponding N2pc difference waveforms computed by subtracting ipsilateral from contralateral ERPs for each cue condition.

Figure 4: Grand averaged difference waveforms obtained on trials where cued nontargets appeared on the left or right and targets on the vertical meridian, computed by subtracting ipsilateral from contralateral ERPs at PO7/8. Difference waves are shown separately for blocks with positive and negative cues.

Figure 5: Grand averaged difference waveforms obtained on trials where targets appeared on the left or right side, computed by subtracting ipsilateral from contralateral ERPs at PO7/8. Difference waves are shown separately for search displays in position 1, 2, and 3 after the cue, for blocks with neutral cues (black lines) and negative cues (grey lines).

Figure 6: Grand averaged difference waveforms obtained for search displays with a negatively cued nontarget on the left or right and a target on the vertical meridian, computed by subtracting ipsilateral from contralateral ERPs at PO7/8. Difference waves are shown separately for search displays at positions 1, 2, and 3 after the cue.

Figure 7: Mean RT data in Experiment 5. Data from negative cue blocks is shown for each block tertile. For comparison, mean RT in neutral cue blocks is included as a straight line. Error bars denote ± 1 SE.

Figure 8: Grand average contralateral-ipsilateral difference waveforms obtained in negative cue blocks in Experiment 5 in the 500 ms interval following search display onset at posterior electrode sites PO7/PO8. Difference waves are shown separately for the three negative cue block tertiles (blocks 1-4, 5-8, 9-12). Left panel: P_D difference waves measured relative to the position of a lateral negatively cued distractor in displays where the search target was presented on the vertical midline. Right panel: N2pc difference waves measured in response to lateral search targets. ERPs are shown separately for each block tertile within the negative condition and the baseline neutral condition.

Figure 1

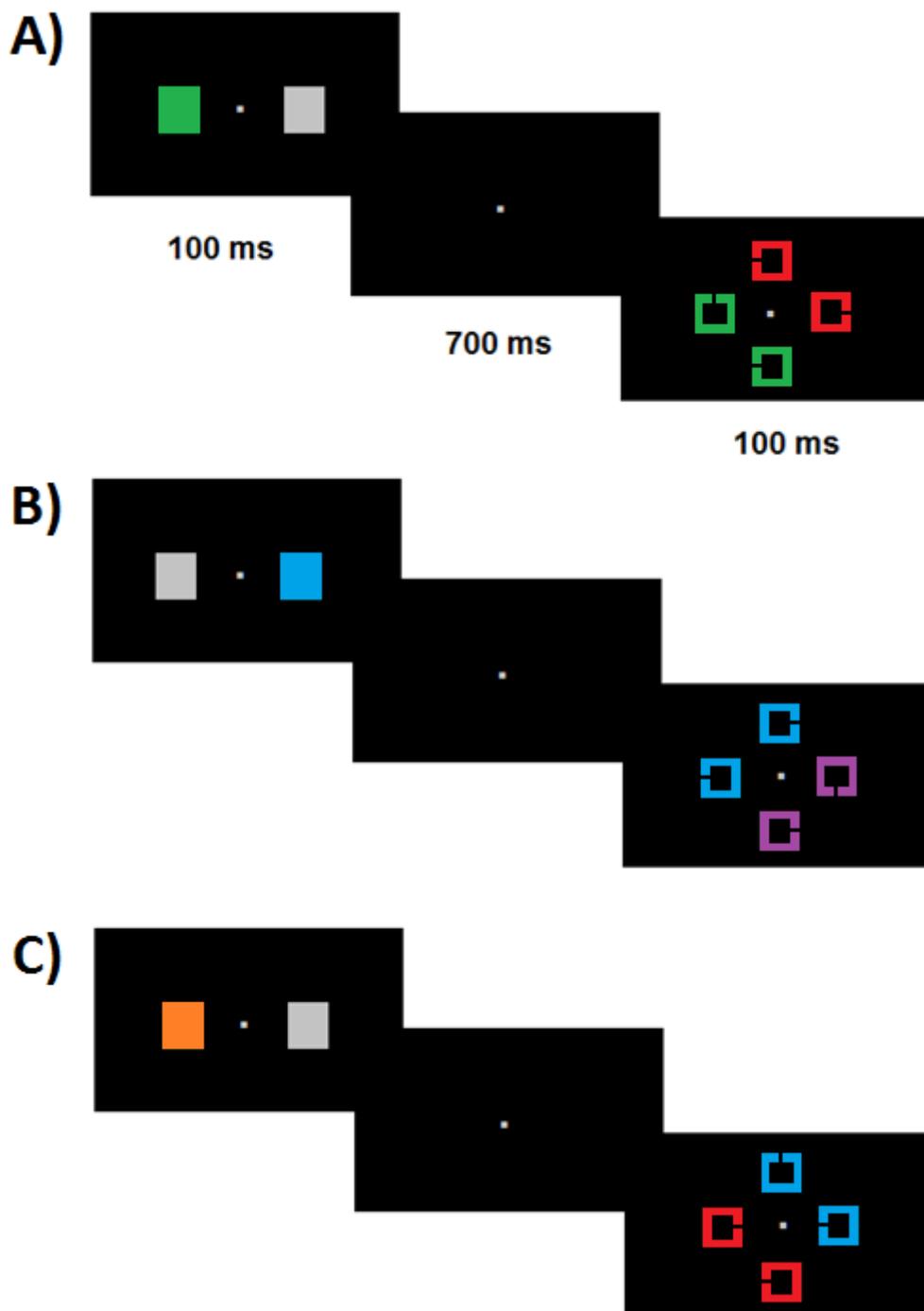


Figure 2

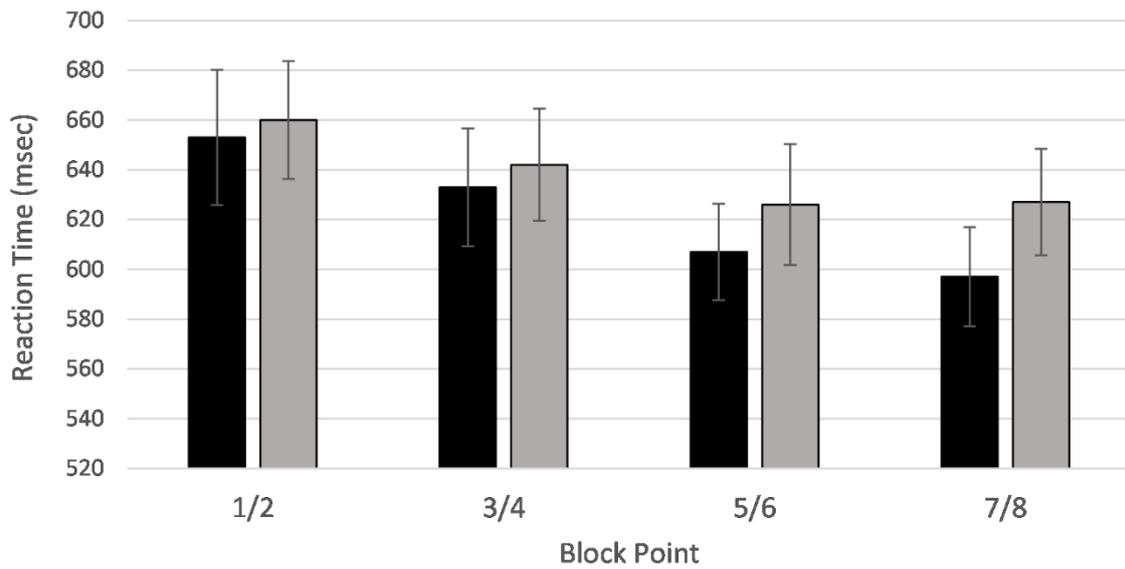
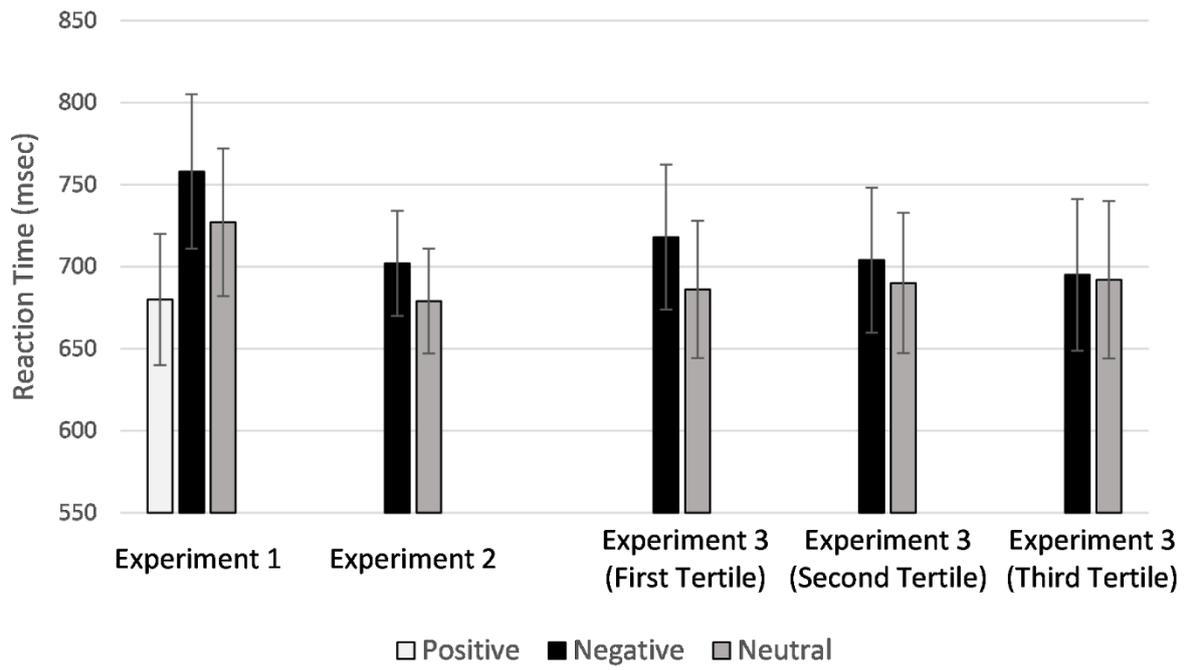


Figure 3

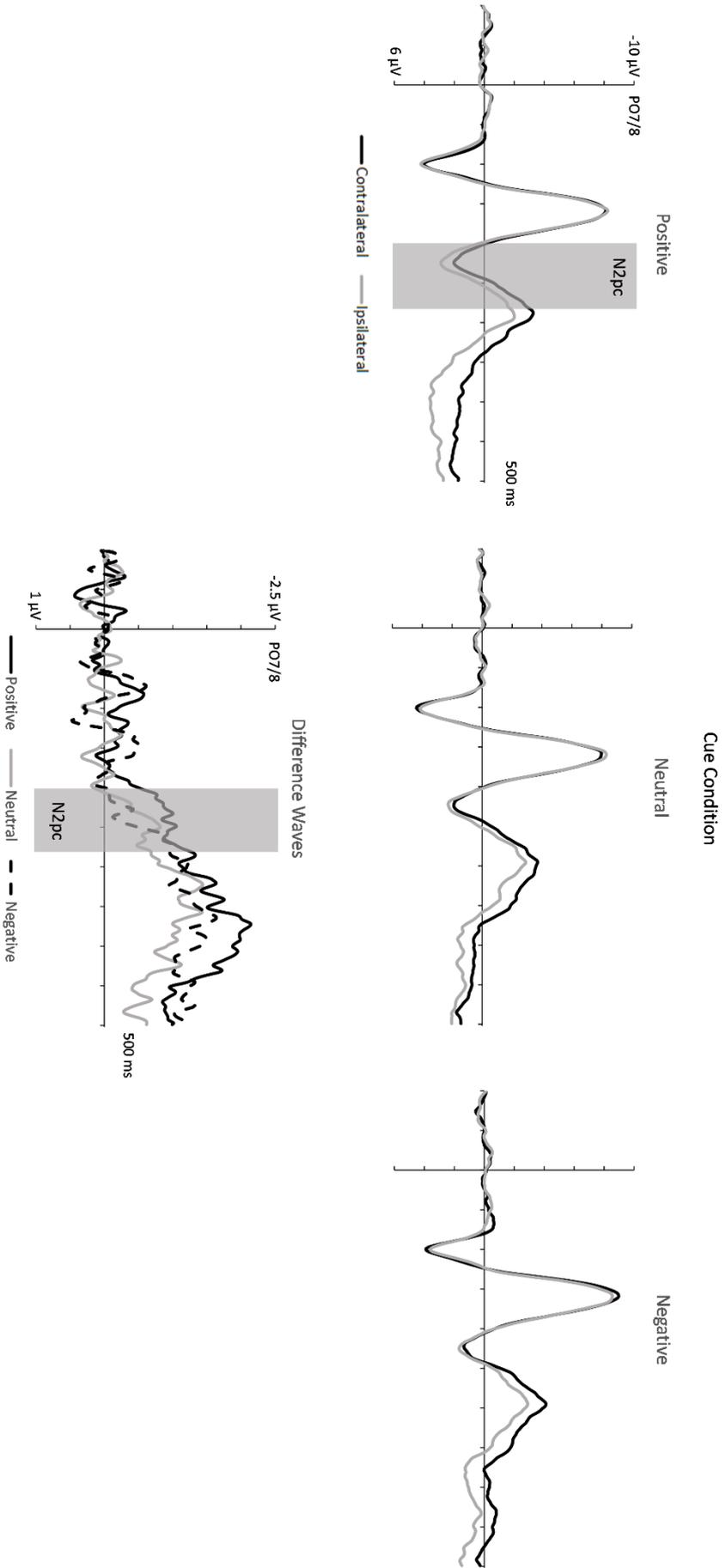


Figure 4

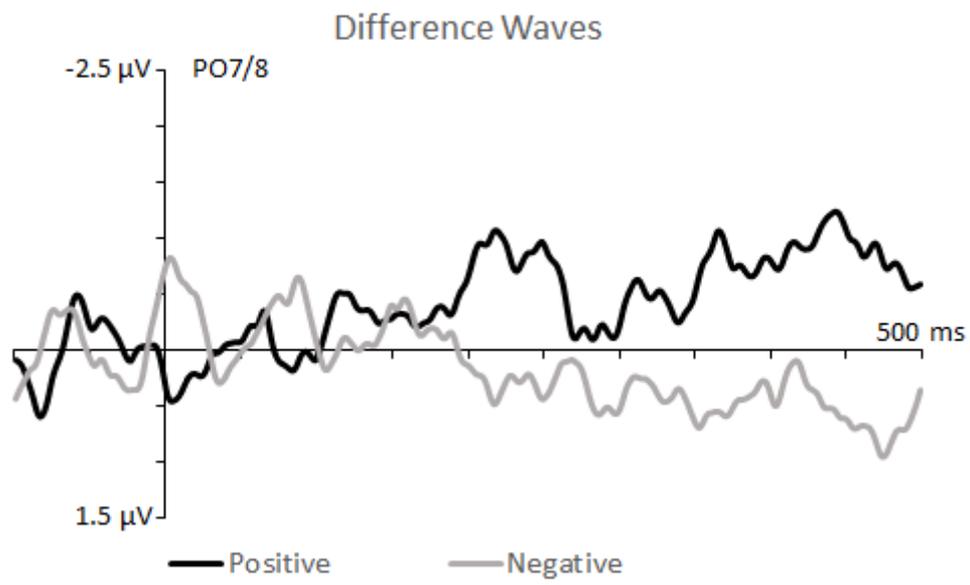


Figure 5

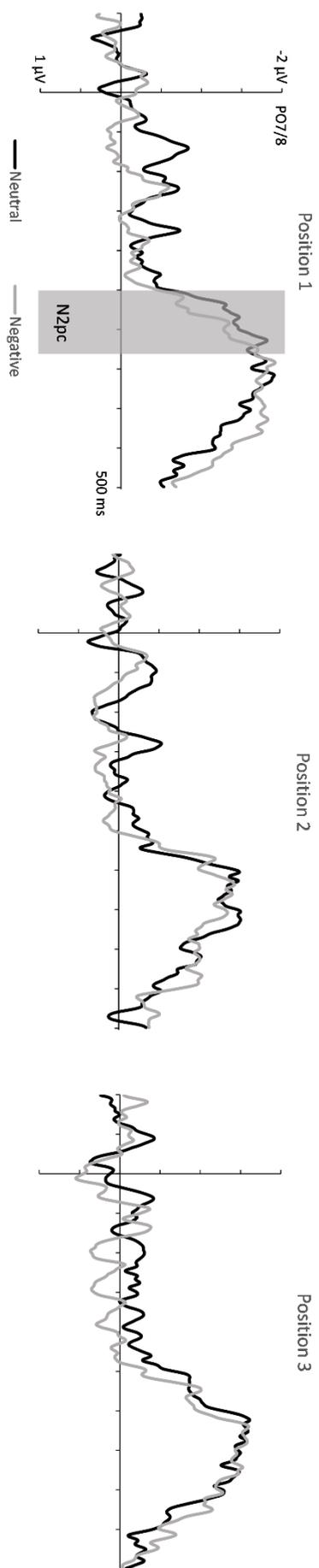


Figure 6

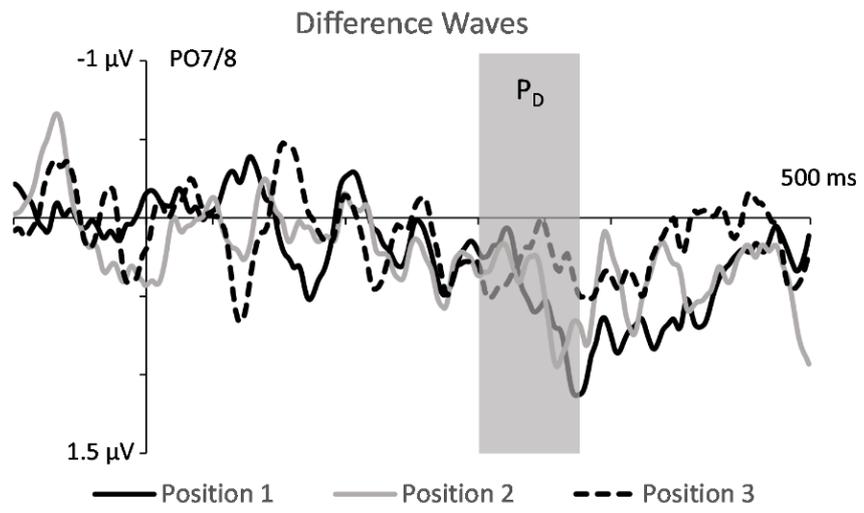


Figure 7

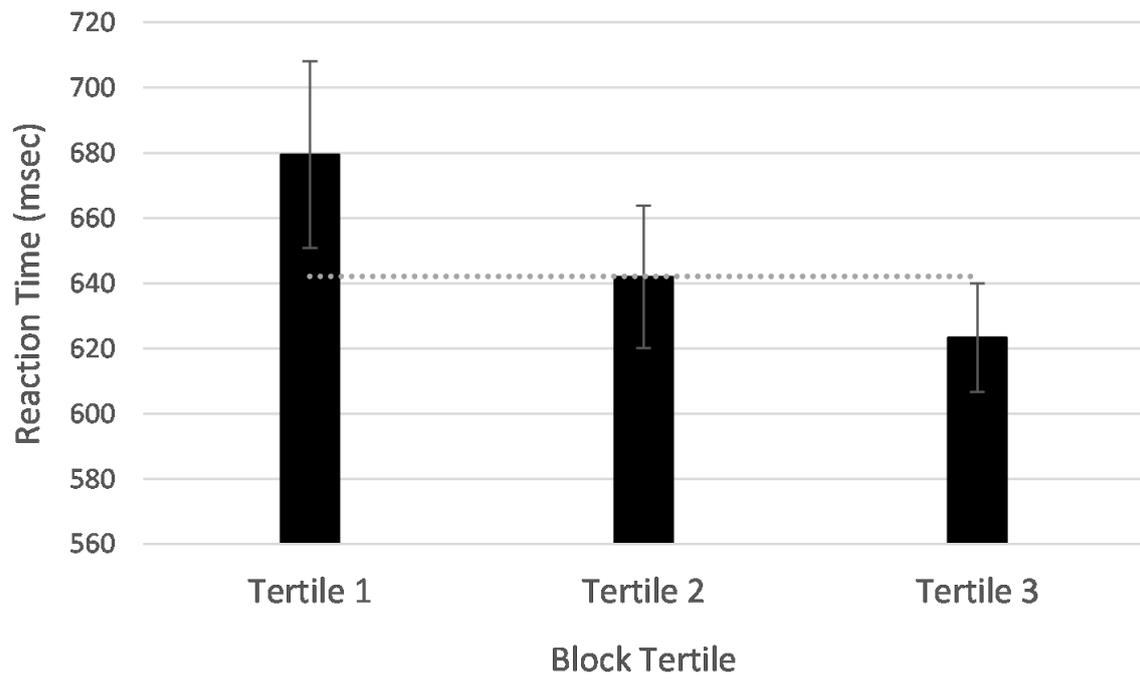


Figure 8

