Do We Prepare for What We Predict? How Target Expectations Affect Preparatory Attentional Templates and Target Selection in Visual Search

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Abstract

■ Visual search is guided by representations of target-defining features (attentional templates) that are activated in a preparatory fashion. Here, we investigated whether these template activation processes are modulated by probabilistic expectations about upcoming search targets. We tracked template activation while observers prepared to search for one or two possible color-defined targets by measuring N2pc components (markers of attentional capture) to task-irrelevant color probes flashed every 200 msec during the interval between search displays. These probes elicit N2pcs only if the corresponding color template is active at the time when the probe appears. Probe N2pcs emerged from about 600 msec before search display onset. They did not differ between one-color and two-color search, indicating that two color templates can be activated concurrently. Critically, probe N2pcs measured during two-color search were identical for probes matching an expected or unexpected color (target color probability: 80% vs. 20%), or one of two equally likely colors. This strongly suggests that probabilistic target color expectations had no impact on search preparation. In marked contrast, subsequent target selection processes were strongly affected by these expectations. We discuss possible explanations for this clear dissociation in the effects of expectations on preparatory search template activation and search target selection, respectively. ■

INTRODUCTION

During visual search, observers have to detect and identify target objects that appear at unpredictable locations among multiple other irrelevant distractors. In these situations, attentional control mechanisms operate to ensure that visual processing is biased toward target objects. The properties of targets are assumed to be represented in attentional templates (Duncan & Humphreys, 1989), which are held in visual working memory (e.g., Olivers, Peters, Houtkamp, & Roelfsema, 2011; Duncan & Humphreys, 1992). It is assumed that attentional templates are activated during the preparation for an impending search episode (e.g., Desimone & Duncan, 1995). Following the arrival of visual input, they will guide attention selectively toward objects with template-matching features (e.g., Wolfe & Horowitz, 2004, 2017).

Preparatory search templates reflect the relevance of specific visual features in a given task context. However, it is unclear whether they are also sensitive to expectations with respect to the probability that these features will be encountered. Relevance is linked to the goal-directed nature of visual search. Because the objective of search is to find and respond to currently task-relevant objects (i.e., targets) rather than irrelevant distractors, preparatory search templates are, by definition, representations of relevance. Expectation is linked to the likelihood that a particular target object will actually be present in an upcoming search display. Previous research has shown that expectations with respect to anticipated target objects can modulate attentional control and selectivity (e.g., Summerfield & de Lange, 2014; Wyart, Nobre, & Summerfield, 2012; Feldman & Friston, 2010). It is therefore plausible to assume that such expectations may be reflected by the relative activation levels of preparatory search templates. However, the question whether and in what way expectation modulates the preparation for visual search has, so far, not been explicitly addressed. One reason for this is that in typical lab-based visual search tasks, where participants prepare to find a single known search target object that appears on every trial, relevance and expectation are inextricably linked. However, expectation and relevance can be dissociated when using search tasks with multiple potential targets, which are all relevant, but can differ in their probability, thus making them more or less expected.

The goal of this study was to investigate the effects of such probabilistic expectations on the activation of attentional templates during the preparation for visual search. Because target-related expectations can only be manipulated in tasks where observers search for one of several possible target objects, the first question is whether multiple preparatory attentional templates can be activated in parallel at all. Some authors have claimed that

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only a single target template can be maintained at any given time (e.g., Olivers et al., 2011; Houtkamp & Roelfsema, 2009). However, other studies have found strong support for the existence of multiple simultaneously active attentional templates. For example, Irons, Folk, and Remington (2012) employed tasks where observers searched for one of two equally likely color-defined targets. Search displays were preceded by spatially uninformative cues that matched either one of the two target colors or a different distractor color. Responses to search targets were faster on trials where a target was presented at the same location as a previous color cue relative to trials where cues and targets appeared at different locations, indicating that the cues captured attention. Critically, such spatial cueing effects were found for both target color cues but not for distractor color cues, suggesting that search templates for both target colors were activated in parallel (see also Beck, Hollingworth, & Luck, 2012; Moore & Weissman, 2010, for additional evidence for multiple search templates).

Although these behavioral effects provide evidence for multiple preparatory attentional templates, observing the activation of such templates directly is challenging. Because these preparation processes occur endogenously in the absence of overt behavior and take place before a search display is presented, they are difficult to track with performance-based measures. However, they can be monitored with brain activity measures that are obtained during the preparation for search. For example, Chelazzi, Duncan, Miller, and Desimone (1998) demonstrated with single-unit recordings from monkeys that representations of anticipated target objects are actively maintained before the presentation of a search display, as reflected by a modulation of the baseline activity of object-selective cells. More recently, we employed noninvasive EEG measures in human observers to track search template activation processes in real time (Grubert & Eimer, 2018). We used a rapid serial probe presentation (RSPP) paradigm, where search displays containing a color-defined target object among multiple distractors were preceded by a series of irrelevant "probes" that appeared sequentially every 200 msec throughout the interval between successive search displays. Critically, each of these probes included a color singleton item that could match the color of the target. These probes should capture attention at times when the target template is activated, but not during periods where this template is inactive. To track probe-induced attentional capture, ERPs were recorded to measure N2pc components to each successive probe presented between two search displays. The N2pc is a negativity at posterior scalp electrodes contralateral to attended objects in multistimulus displays that emerges around 180–200 msec after stimulus onset. It is generated in ventral extrastriate visual areas (Hopf et al., 2000) and reflects the rapid allocation of attention to candidate target objects (e.g., Woodman & Luck, 1999; Eimer, 1996; Luck & Hillyard, 1994; see Eimer, 2014, for a review). Importantly, N2pcs are also triggered by task-irrelevant objects when their features match a currently active search template (e.g., Eimer & Kiss, 2008; Lien, Ruthruff, Goodin, & Remington, 2008). In our previous study (Grubert & Eimer, 2018), singleton probes that matched the current target color triggered reliable N2pc components from about 1000 msec before the onset of the next search display, whereas no such N2pcs were elicited by singleton probes in a different nontarget color. These observations suggest that color-selective search templates were activated in a transient fashion during the preparation for search. The timing of probe N2pcs changed when the predictable interval between two search displays was manipulated. They were triggered soon after the offset of the preceding search display when this interval was short and much later during the preparation interval in blocks with longer intervals. This indicates that search template activation processes can be tuned to expectations about the arrival time of target objects (see also Olmos-Solis, van Loon, Los, & Olivers, 2017, for analogous findings for eye movements).

Because observers always searched for a single constant target object in this study (Grubert & Eimer, 2018), its results do not offer any insights into whether multiple preparatory search templates can be activated concurrently. In a follow-up study (Grubert & Eimer, 2020), we used similar RSPP procedures but now included two possible color-defined search targets that alternated between trials in a fully predictable fashion (ABAB). N2pcs were measured separately for singleton probes that matched the upcoming (now relevant) or the preceding (now irrelevant) target color. Reliable N2pcs were triggered by both types of probes from 1000 msec before search display onset, thus providing online electrophysiological evidence for the simultaneous activation of two color-specific search templates. Importantly, predictions about the upcoming target color modulated N2pcs only for probes that appeared immediately before the arrival of the search display, when N2pcs were larger for probes that matched the upcoming target color relative to probes in the other currently irrelevant color.

The observation that both color templates were activated even when the color of the next target object was fully predictable points to important limitations in the impact of target-related expectations on the selectivity of preparatory attentional control processes. The goal of this study was to investigate the effects of expectation of the activation of attentional search templates more systematically. Here, we focused on probabilistic expectations by manipulating the likelihood of particular color-defined target objects. We employed the same general RSPP paradigm as in our previous research (Grubert & Eimer, 2018, 2020), but now systematically varied both the number of possible search targets (one-color vs. two-color search), and also, critically, the probability of each color target object in two-color search (80–20%, 50–50%). As before, color singleton probes were presented every

200 msec during the interval between two search displays (see Figure 1). N2pc components elicited by these color probes were computed separately for probes at each temporal position between two search displays. In addition, N2pcs triggered by target objects in search displays were also measured. There were three blocked task conditions. In the one-color task, participants searched for one constant target color, as in our original study (Grubert & Eimer, 2018). All singleton probes in this task matched the target color. In the two-color 50/50 task, there were two possible color-defined targets, and search displays were equally likely to include either of these targets. In the two-color 80/20 task, there was one frequent (expected) target color that appeared in 80% of all search displays, and there was another rare (unexpected) target color that was shown in the remaining 20%. In both two-color tasks, each probe display included one of these two colors, which appeared in random order and with equal probability.

The first set of analyses focused on differences in preparatory template activation processes between search for a single target color and for one of two equally likely target colors to further confirm that two search templates can be activated concurrently. In the one-color task, where only a single target template was required, the time course of probe N2pcs should be similar to our previous results (Grubert & Eimer, 2018), with reliable N2pcs to target-matching probes emerging from around 1000 msec before the onset of the next search display. If two color templates can be activated simultaneously (e.g., Grubert & Eimer, 2020; Irons et al., 2012), a similar pattern of probe N2pcs should be observed in the two-color 50/50 task. However, competitive interactions between these templates (see Ort & Olivers, 2020, for discussion) could affect the time course and the magnitude of template activation processes. In this case, probe N2pc components may be smaller and possibly emerge later during the interval between two search displays in the two-color 50/50 task relative to the one-color task.

The main set of analyses investigated our primary question about the effects of probabilistic expectations on preparatory template activation. In the two-color 50/50

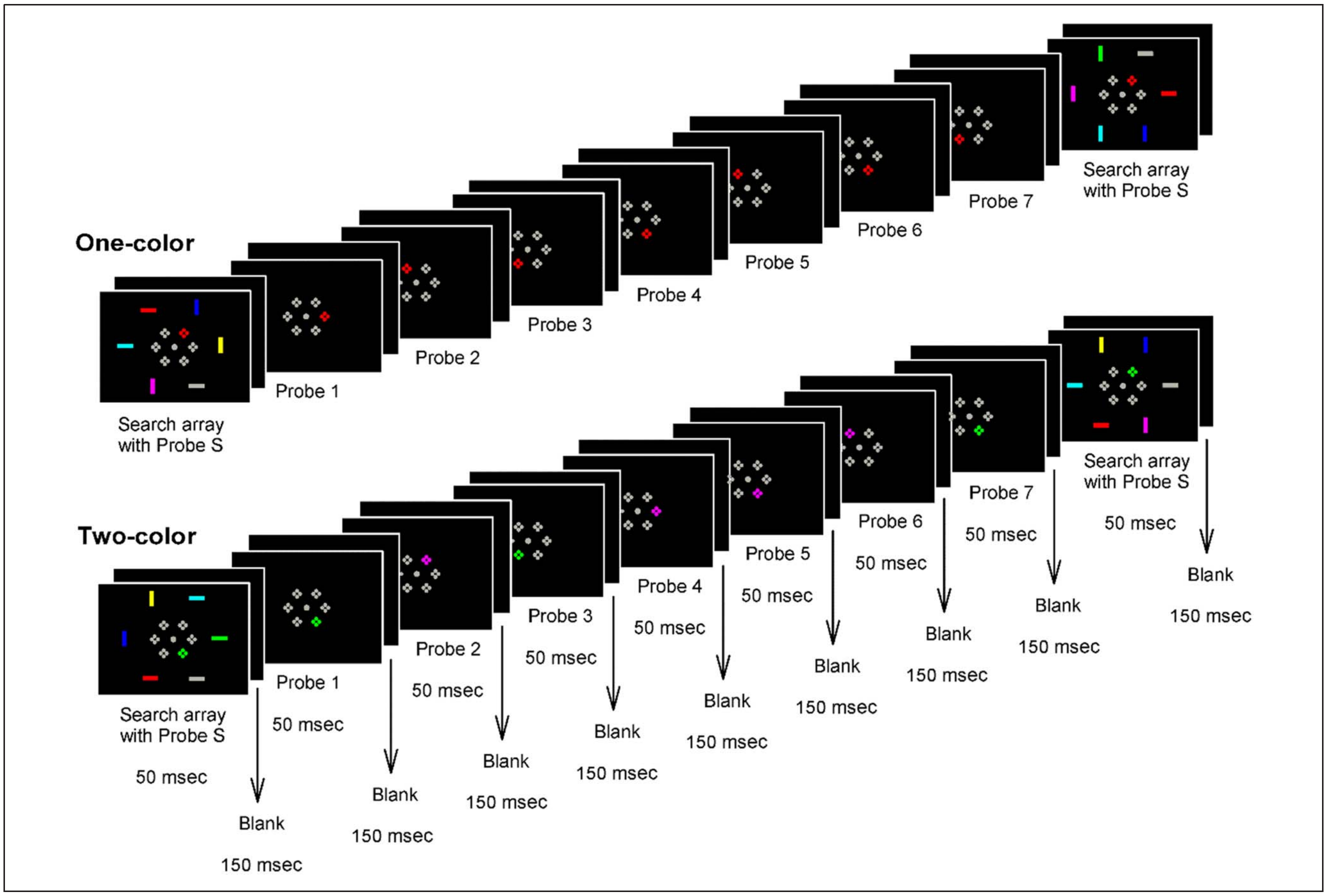

Figure 1. Schematic illustrations of the time course of stimulus events in the one-color (top) and two-color (bottom) tasks of Experiment 1. Search displays included a color-defined target bar and five distractor bars in five different nontarget colors. In probe displays, a target color singleton probe appeared among five gray items. Probe displays were presented every 200 msec in the interval between two search displays (Probes 1–7) and simultaneously with a search display (Probe S). The items in the probe and search displays were arranged in a circular fashion, at an eccentricity of 0.5° (probe displays) and 1.4° (search displays) from central fixation. In Experiment 2 (not shown here), probe displays contained one of four possible color singletons (matching one of the two target and one of two possible distractor colors).

task, both color targets were equally likely and thus equally expected. In the two-color 80/20 task, one target color was frequent and the other target color was infrequent, making the respective colors highly expected versus unexpected. The question was whether and how the temporal profile of template activation processes for each target color would reflect these differential expectations. To test this, we compared N2pcs to probes that matched either the expected or unexpected target color in the two-color 80/20 task and also compared these probe N2pcs to the N2pcs measured in the two-color 50/50 task. If the activation profile of attentional templates is adjusted in line with probabilistic expectations about the likelihood that a specific target will be encountered during the next search episode, N2pc components for probes that match a more frequent target color should be larger and possibly emerge earlier during search preparation than N2pcs elicited by probes that match a less expected target color. Alternatively, if preparatory search templates are insensitive to such expectations, the time course and the amplitudes of N2pc components to these probes should not be affected by the manipulation of target color probabilities. Because the absence of such probability-related effects would be theoretically important, we employed Bayesian statistics to evaluate the strength of any empirical evidence in favor of the null hypothesis.

EXPERIMENT 1

Methods

Participants

Nineteen paid participants took part in Experiment 1. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Psychology Ethics Committee at Durham University. All participants gave informed written consent before testing. Three participants were excluded from the sample because of excessive eye movement activity, resulting in a loss of more than 40% of all data after EEG artifact rejection. One additional participant was excluded because of high error rates (>40%). The remaining 15 participants were aged between 24 and 38 years (mean = 32.3 years, *SD* = 4.6 years). Eleven were female, and one was left-handed. All had normal or corrected-to-normal vision and no color vision deficiencies (as tested with the Ishihara color vision test; Ishihara, 1972). The required sample size of 15 was determined based on an a priori power analysis (G*Power; Faul, Erdfelder, Buchner, & Lang, 2009), with an assumed alpha of .05, power ($1 - \beta$) of .95, and an effect size (f) of 1.08 (determined according to Cohen, 1988). This effect size was originally measured in Experiment 1 of Grubert and Eimer (2018; p. 9532; $\eta_p^2 = .54$) for N2pc amplitudes triggered by target color probes (main effect of laterality across all successive probes) in the RSPP paradigm.

Stimuli and Procedures

Participants were seated in a dimly lit and sound-attenuated Faraday cage. They viewed the stimuli on a 24-in. BenQ GL2450HE HD monitor (1280 × 1024 pixels resolution, 100 Hz refresh rate) at a distance of approximately 100 cm. A 3.3-GHz quad-core processor (running on Windows 7) controlled stimulus presentation, timing, and response collection, using MATLAB and the Cogent 2000 toolbox. Figure 1 illustrates the general time course of stimulus events. All stimuli were presented on a black background that contained a constant central gray fixation point (CIE x, y color coordinates: .299/.314; 0.2° × 0.2° of visual angle). Each trial included eight consecutive circular stimulus displays that were each presented for 50 msec and were separated by a blank 150-msec interval (200 msec SOA). The first seven displays in each trial each contained a probe array (Probes 1–7). The eighth displays contained both the task-relevant search array and a probe array (simultaneous probe/search: Probe S). A Probe S was included on each trial to make probe onset completely regular (every 200 msec) within each experimental block. Probe arrays were presented closer to fixation than search arrays. The blank interval between the offset of the probe/search display on the preceding trial and the onset of the first probe display on the next trial was also 150 msec, resulting in a continuous serial presentation stream of stimuli within each block.

Search arrays contained six vertical or horizontal bars (0.2° × 0.6° each) at the 1, 3, 5, 7, 9, and 11 o'clock positions of an imaginary clock face, at an eccentricity of 1.4° from central fixation. The six bar orientations in each trial were selected independently and randomly. Each bar was shown in a different color. There were seven possible stimulus colors: red (.635/.329), green (.291/.599), blue (.155/.086), yellow (.471/.458), cyan (.214/.308), pink (.265/.142), and gray (.299/.314). All colors were equiluminant (~9.3 cd/m^2). One bar was presented in a predefined target color, and the five other bars were presented in five randomly assigned nontarget colors. For counterbalancing reasons (see below), only five of the seven colors were used as target colors (red, green, blue, yellow, and pink); the other two (cyan and gray) always only served as nontarget colors. The location of the target bar was selected randomly in each trial, with the constraint that within each block of trials, targets appeared equally often in the left and right hemifield.

Probe arrays contained six items composed of four closely aligned dots (0.1° × 0.1° each; two on the vertical, and two on the horizontal axis; total size of each four-dot probe item: 0.25° × 0.25°). They were presented at the 1, 3, 5, 7, 9, and 11 o'clock positions of an imaginary clock face, at an eccentricity of 0.5° from central fixation. One of the items in each probe display was a target color singleton; the other five items were uniformly gray. The color probe location was selected independently for each probe display, with the restriction that there were no immediate location repetitions across consecutive displays and that successive probes would equally likely appear on the same or opposite display side (to ensure that, on average, each probe was preceded equally often by a probe on the same or opposite display side). Participants were informed that probe displays were response-irrelevant and should be entirely ignored.

There were three blocked task conditions in Experiment 1. In all three tasks, participants had to report the orientation of the target color bar in the search array (vertical, horizontal) on a standard keyboard by pressing the arrow up or down key, respectively. The response-to-key mapping (vertical/horizontal response on top/bottom key) and the hand-to-key mapping (left/right hand on top/bottom key) was counterbalanced across participants but was kept constant for each participant for the duration of the whole experiment. In the one-color task (Figure 1, top panel), search targets were defined by a single color (e.g., red) that remained constant throughout. Each of the five possible target colors (red, green, blue, yellow, and pink) served as target color for three participants. Each probe display contained a color singleton item that matched this target color. In the two-color tasks, search arrays contained one of two possible color-defined targets (e.g., a green or a pink bar). Each of these two-color targets was equally likely to appear in a search array in the two-color 50/50 task. In the two-color 80/20 task, however, one color target was frequent, appearing in 80% of all search arrays, whereas the other rare color target was presented in only 20% of these arrays. Participants were informed about the target color probabilities in these two tasks. Two different pairs of target-defining colors were chosen for each participant for these two tasks, and these colors differed from the target color assigned to the same participant in the one-color task. Pairs of target colors were always nonadjacent on the color wheel (i.e., red or green, red or blue, green or pink, yellow or pink, and blue or yellow). The assignment of these five target color pairs in both two-color tasks was counterbalanced across participants, but for each participant remained the same throughout the respective task. Across the whole experiment, each of the five possible target colors was used equally often as the target color in the one-color task; as one of the two colors in the two-color 50/50 task; and as frequent and rare color, respectively, in the two-color 80/20 task. In both two-color tasks, singleton probes that matched either of the two target colors appeared randomly and equiprobably (Figure 1, bottom panel).

Experiment 1 contained 100 blocks (20 for the one-color task and 40 for each of the two-color tasks), with 10 trials per block (for a total of 200 trials per target color in each task). Blocks were short to minimize the presence of blinks within each block. In each block, the 10th search display was followed by seven additional probe displays to keep response conditions identical across all trials in a block. Consequently, each block contained 10 search displays and 87 probe displays (11 for Probes 1–7 and 10 for Probe S, which was presented together with the search display). Before each task condition, participants received two practice blocks where EEG was not recorded.

EEG Recording and Data Analyses

EEG was DC-recorded from 24 scalp sites (standard positions of the extended 10/20 system), sampled at 500 Hz, and digitally low-pass filtered at 40 Hz (no other filters were applied after data acquisition). Impedances were kept below 5 kΩ. The left earlobe served as online reference during data acquisition, but all channels were re-referenced off-line to linked earlobes. EEG was segmented into 500-msec time windows, including a 100-msec prestimulus baseline and a 400-msec ERP time window following the onset of a particular stimulus display (Probes 1–7, search array, and Probe S). Data from the first and last seven probe displays in each block and trials with anticipatory (<200 msec), very slow (>1500 msec), and missing or incorrect responses did not enter analysis. Furthermore, data contaminated with artifacts (eye movements exceeding ±30 μV in the bipolar HEOG channel, blinks exceeding ±60 μV at Fpz, muscular movements exceeding ±80 μV in all other channels) were excluded from EEG analyses. Artifact rejection resulted in an exclusion of 5.4% (*SD* = 7.3%) of all epochs in the one-color task (ranging between 0.3% and 29.2% across participants), 7.3% (*SD* = 10.4%) in the two-color 50/50 task (0.6–36.4%), and 7.2% (*SD* = 9.4%) in the two-color 80/20 task (0.6–37.7%). Of the remaining epochs, different averages were computed for all probe displays (Probes 1 to S, where Probe 1 was the probe that immediately followed the preceding search display and Probe S was the probe that was presented simultaneously with the search display in a trial), separately for the three tasks, and for probe displays with a color singleton item in the left or right hemifield, respectively. For both two-color tasks, separate averages were additionally generated for singleton probe displays that matched either target color. Additional separate averages were also computed for search displays with a target in the left or right hemifield.

N2pc components to probes were quantified based on ERP mean amplitudes obtained at lateral posterior electrodes PO7 and PO8, contralateral and ipsilateral to the side of a probe, within an 80-msec time window starting at 210 msec after the respective probe display onset. As in our previous work using analogous RSPP procedures (Grubert & Eimer, 2018), the start of this time window was determined by measuring the point in time (rounded to the nearest 10) when the ascending flank of the averaged probe N2pc (pooled across all probes in all conditions of Experiment 1) reached 50% of the peak amplitude (at −0.13 μV). N2pc components to target bars in the search displays were computed within the same 210–290 msec poststimulus time window used for the probe N2pc analyses. In addition to mean amplitudes, target N2pc onset differences were assessed by means of jackknife-based onset latency analyses (Miller, Patterson, & Ulrich, 1998) on N2pc difference waveforms (subtraction of ipsilateral from contralateral ERPs at PO7 and PO8). Fifteen grand-averaged difference waves were computed for each experimental condition, each excluding one different participant from the original sample. N2pc onset latency was defined as the point in time when each subsample difference wave reached an absolute onset criterion of −0.9 μV (50% of the peak amplitude of the averaged target N2pc, pooled across all targets in all conditions of Experiment 1). All t tests on jackknifed N2pc onset latencies were power-corrected as suggested by Miller et al. (1998) and are denoted with t_c. All t tests reported are two-tailed. Effect sizes are reported in terms of Cohen's d (Cohen, 1988), with a confidence interval of 95%, for t tests and partial eta squared (η_p^2) for F tests and power-corrected t_c tests. Bayesian statistics (Rouder, Speckman, Sun, Morey, & Iverson, 2009) were used in JASP to evaluate empirical evidence in favor of the null hypothesis. Substantial evidence for the null hypothesis is marked by Bayes factors (BF_{01}) > 3 (Jeffreys, 1961), indicating that the empirical data are more than three times more likely under the null hypothesis as compared with the alternative hypothesis.

Results

Behavioral Results

Across all three tasks, less than 0.2% of all trials were excluded as anticipatory (<200 msec) or very slow (>1500 msec) responses. For mean correct RTs, there was a main effect of Task, $F(2, 28) = 7.8, p = .002, \eta_p^2 = .36$, as RTs were faster in the one-color task (584 msec) relative to the two-color 50/50 task (662 msec) and the two-color 80/20 task (670 msec). For error rates, there was also a main effect of Task, $F(2, 28) = 4.7, p = .017, \eta_p^2 = .25$, as errors were less frequent in the one-color task (3.8%) relative to the two-color 50/50 task (8.0%) and the two-color 80/20 task (7.1%). Additional independent t tests revealed that relative to the two-color 50/50 and 80/20 tasks, mean correct RTs in the one-color task were faster, both $t(14) \geq 2.8, p \leq .014, d \geq 0.91$, and error rates were lower, both $t(14) \geq 2.4, p \leq .029, d \geq 0.84$. Error rates and RTs were not reliably different between the two two-color tasks, both $t(14) < 1$. In the two-color 80/20 task, RTs were slower for targets in the rare color relative to targets in the frequent color (701 msec vs. 639 msec), $t(14) = 3.4, p = .004, d = 0.64$, but error rates did not differ reliably between these two types of targets (7.8% vs. 6.3%), $t(14) < 1$.

N2pc Components

The overall pattern of ERP activity elicited at posterior electrode sites PO7/8 by search and probe displays in this RSPP task is illustrated in Figure 2, which shows grand-averaged ERPs to two successive search displays and intermediate probe displays across all trials in the one-color task. Waveforms are shown separately for electrodes contralateral and ipsilateral to the target color bar in the second search display. Large visual P1 and N1 components were triggered by both search displays, and much smaller P1 and N1 components were elicited by each of the seven probe displays in the interval between successive search displays (probe display onsets are indicated by vertical lines). A clear target N2pc component is evident for the second search display. Because the locations of two successive targets and the location of all intermediate color probes were determined independently, no probe N2pcs and no N2pc to targets in the first search display are present in Figure 2.

Single-template versus Multiple-template Activation in the One-color and Two-color 50/50 Task

To compare the time course of target selection and search template activation processes during single-color versus two-color search, target and probe N2pcs were compared between the one-color and the two-color 50/50 task. The left panels of Figure 3 show ERPs triggered by search displays at electrodes PO7/8 contralateral and ipsilateral to the side of the target color bar in the one-color and two-color 50/50 tasks. Figure 3 (right) shows the resulting target N2pc difference waveforms, obtained by subtracting ipsilateral from contralateral ERPs. Target N2pcs were smaller and emerged later in the two-color task relative to the one-color task. This was confirmed by a repeated-measures ANOVA on N2pc mean amplitudes with the factors Task (one-color, two-color 50/50) and Laterality (electrode ipsilateral, contralateral to the side of the target). A main effect of Laterality, $F(1, 14) = 235.8, p < .001, \eta_p^2 = .94$, reflecting the presence of reliable target N2pc components, was accompanied by a significant interaction, $F(1, 14) = 30.4, p < .001, \eta_p^2 = .69$, as target N2pc amplitudes were smaller in the two-color 50/50 task (−1.2 μV) relative to the one-color task (−1.8 μV). Independent follow-up t tests comparing ipsi- and contralateral ERPs in the 210–290 msec poststimulus time window confirmed that target N2pcs were reliably present in both tasks, both $t(14) \geq 8.8, p < .001, d \geq 0.48$. Jackknifed onset latency analyses confirmed that target N2pcs emerged later in the two-color 50/50 task than in the one-color task (231 msec vs. 203 msec), $t_c(14) = 3.1, p = .008, \eta_p^2 = .41$.

N2pcs elicited by target color probes in the one-color and two-color 50/50 tasks were extracted by computing ERPs at posterior sites PO7/8,[1] contralateral and ipsilateral to the side of a probe, separately for each of the eight successive probes in a trial (Probes 1 to S).[2] The resulting ERP waveforms are shown in Figure 4A. To visualize the time course of successive probe N2pcs in these two tasks more intuitively, Figure 4B depicts probe N2pc difference

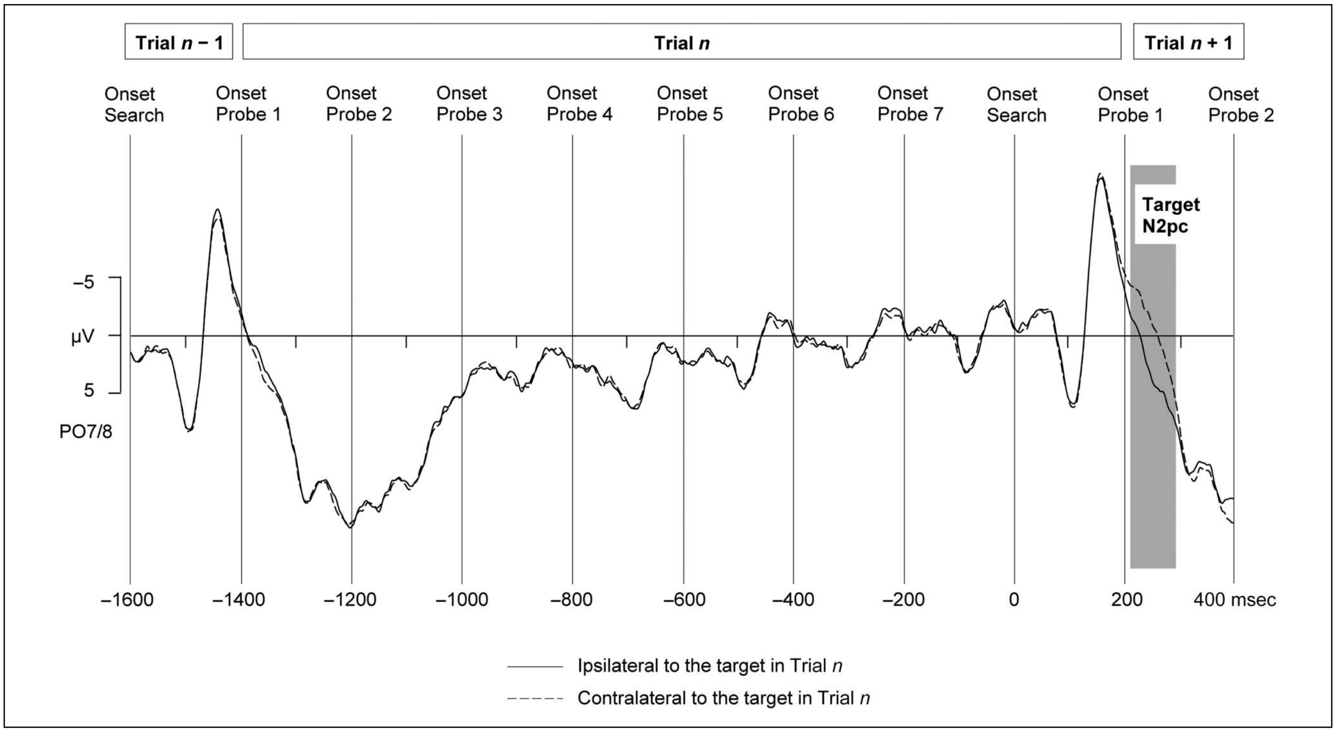

Figure 2. Grand-averaged ERPs elicited in the one-color task of Experiment 1 at electrodes PO7/8 in response to two successive search displays and the probe displays presented in the interval between these displays, collapsed across all trials. Waveforms are shown for electrodes contralateral and ipsilateral to the target color bar in the second search display. Note that this figure only illustrates the overall pattern of ERPs between two search episodes—all statistical analyses of probe N2pcs were conducted relative to the side of the color singleton in each individual probe display. The shaded areas indicate the target N2pc time window (210–290 msec poststimulus).

waveforms (obtained by subtracting ipsi- from contralateral ERPs at PO7/8) in the one-color (top panel) and two-color 50/50 task (bottom panel) in a temporally continuous fashion. For Probe 1, the complete interval from 100 msec before to 350 msec after probe onset is displayed. For all other probes, the time interval shown is from 150 to 350 msec after probe onset. Plots for two successive probe intervals are interpolated between adjacent data points. The onset of each probe is marked with vertical lines, and the N2pc time windows for each probe (210–290 msec post-stimulus) are indicated with gray bars. Because probes were presented every 200 msec, the onset of each individual probe coincides with the N2pc time interval for the preceding probe. As is evident in Figure 4B, target color probes that appeared simultaneously with or immediately after a search display (Probes

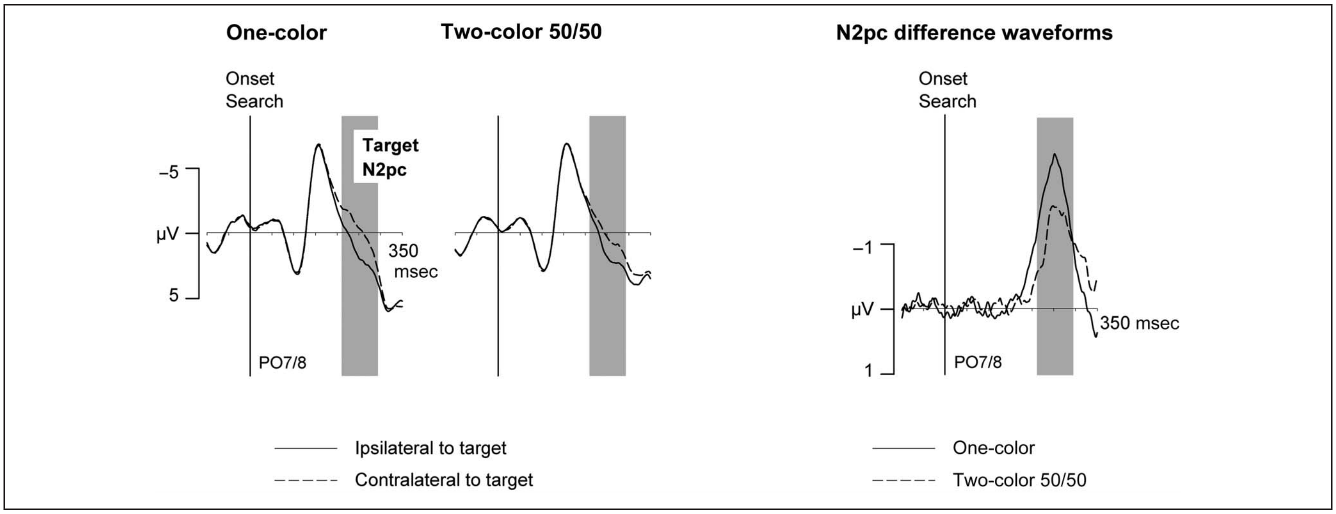

Figure 3. Grand-averaged ERPs elicited by search displays in the one-color and two-color 50/50 tasks of Experiment 1 at electrodes PO7/8 contralateral and ipsilateral to the target (left), together with the corresponding contralateral-ipsilateral N2pc difference waveforms (right). Shaded areas indicate N2pc time windows (210–290 msec after search display onset).

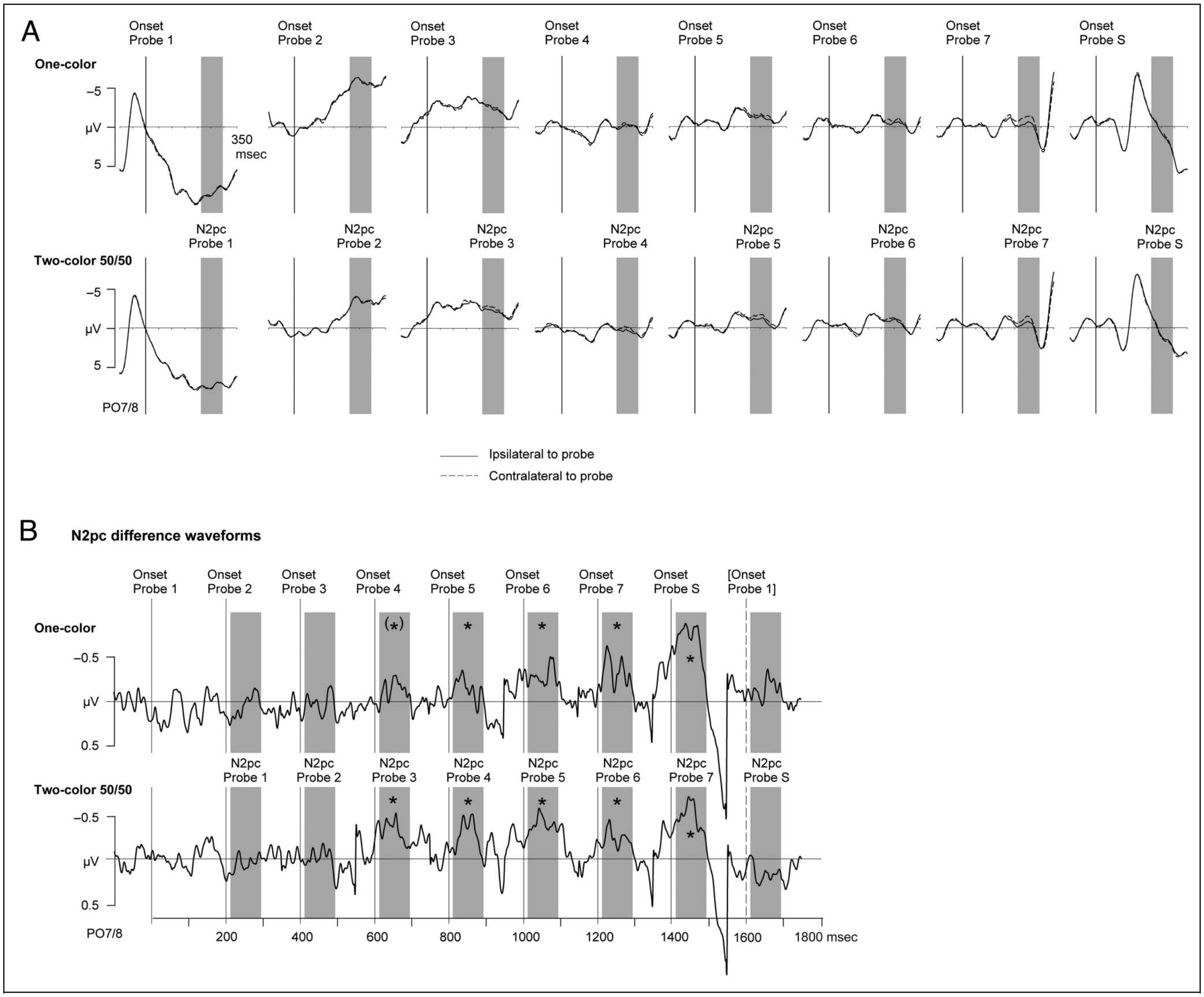

Figure 4. (A) Grand-averaged ERPs elicited in the one-color and two-color 50/50 tasks of Experiment 1 at electrodes PO7/8 contralateral and ipsilateral to color singleton probes. ERPs are shown separately for each temporal position of these probe displays (from Probe 1 to Probe S). (B) N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for each successive color singleton probe, shown separately for the one-color (top) and two-color 50/50 tasks (bottom). Difference waves are shown in a temporally continuous fashion, for 200 msec poststimulus time segments (150–350 msec after probe onset). Probe onsets are indicated by vertical lines, and probe N2pc time windows are indicated by shaded areas. Note that the onset of each probe coincides with the N2pc window for the preceding probe. Statistically reliable probe N2pcs are marked by asterisks. In all panels, shaded areas indicate N2pc time windows for each probe (210–290 msec after probe onset).

S, 1, and 2) did not elicit any N2pc components. N2pcs started to emerge from Probe 3 onward and were largest in amplitude for Probe 7, immediately before the onset of the upcoming search display. Critically, Figure 4B suggests that the amplitudes and the temporal pattern of probe N2pc components was virtually identical for the one-color and two-color 50/50 tasks. These results are further illustrated in Figure 5 (top panel), which shows a bar plot of all probe N2pc mean amplitudes measured in Experiment 1. Probe N2pc amplitudes for the one-color and two-color 50/50 tasks are shown as red and orange bars, respectively.

These observations were statistically confirmed in an omnibus repeated-measures ANOVA on probe N2pc mean amplitudes with the factors Task (one-color, two-color 50/50), Probe Number (Probes 1–7, Probe S), and Laterality (electrode ipsilateral, contralateral to the side of the probe). There was a main effect of Laterality, $F(1, 14) = 37.5, p < .001, \eta_p^2 = .73$, confirming the presence of reliable probe N2pc components. An interaction of Laterality and Probe Number, $F(7, 98) = 15.9, p < .001, \eta_p^2 = .53$, indicated that N2pc components differed between probes at different temporal positions during the interval between two search displays. Importantly, there was no interaction between Laterality and Task, $F(1, 14) < .1$, $p = .728, \eta_p^2 = .01$, suggesting that probe N2pcs of equivalent size were elicited in the one-color and two-color 50/50 tasks. Further support for this conclusion was

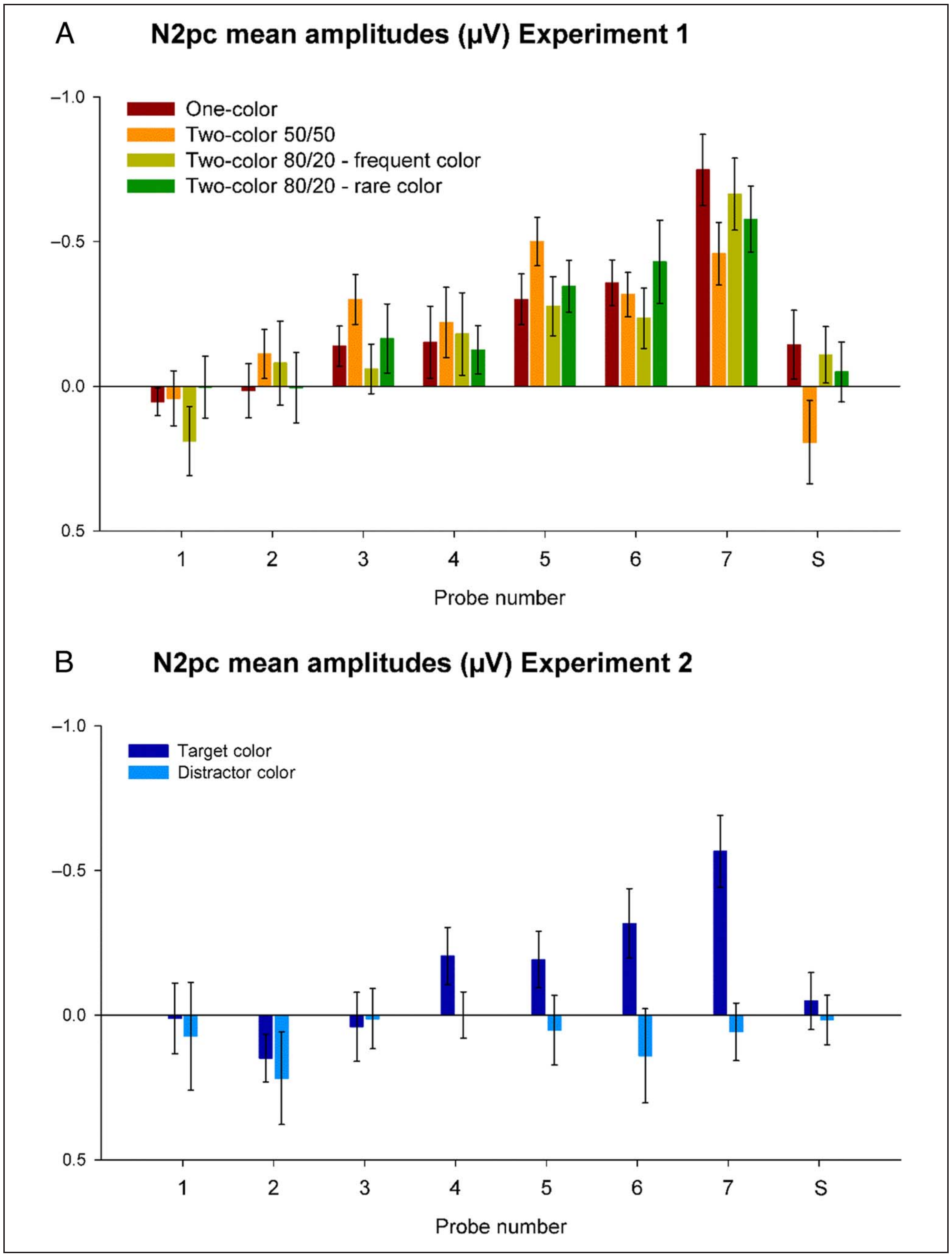

Figure 5. Probe N2pc mean amplitudes obtained in Experiments 1 (A) and 2 (B). Error bars represent the *SEM*.

provided by the corresponding Bayes factor for this interaction, $BF_{01} = 4.8$. However, a three-way interaction between Laterality, Task, and Probe Number was present, $F(7, 98) = 2.2$, $p = .038$, $\eta_p^2 = .14$.[3] To explore whether the time course of probe N2pcs differed systematically between the two tasks, follow-up ANOVAs with the factors Task and Laterality were conducted separately for each temporal probe position (Probes 1 to S). For Probes 1, 2, and S, there were no effects of Laterality, all $F(1, 14) \leq 1.4$, $p \geq .257$, $\eta_p^2 \leq .09$, confirming that these probes did not trigger any N2pcs. In contrast, Laterality main effects were observed for Probes 3–7, all $F(1, 14) \geq 9.2$, $p \leq .009$, $\eta_p^2 \geq .40$. An interaction between Task and Laterality was only present for Probe 3, $F(1, 14) = 6.5$, $p = .023$, $\eta_p^2 = .32$. Follow-up *t* tests comparing contralateral and ipsilateral ERP mean amplitudes in the N2pc time window revealed that this probe elicited a reliable N2pc in the two-color 50/50 task, $t(14) = 4.9$, $p < .001$, $d = 0.24$, but only a marginally significant N2pc in the one-color task, $t(14) = 2.0$, $p = .065$, $d < 0.01$.[4]

One difference between the one-color and two-color 50/50 tasks was that all singleton probes shared the same color in the former task, whereas two randomly intermixed probe colors were used in the latter. This might have resulted in differential probe color adaptation or priming effects, which could have affected probe N2pc components in these two tasks. Adaptation would result in a reduction of N2pcs amplitudes for probes that matched the color of the immediately preceding probe (color repetition) relative to probes that were preceded by a probe in a different color (color change), whereas priming would result in the opposite effect (larger N2pcs for color repetitions). To assess this, we computed N2pcs to all probes in the two-color 50/50 task, separately for color repetitions and changes. An ANOVA of probe N2pc amplitudes with the factors Laterality, Probe Number, and the new additional factor Preceding Probe Color (same vs. different) was conducted. Any color priming or short-term color adaptation should result in probe N2pc differences between color repetitions versus color changes, and this should be reflected in a significant interaction between Laterality and Preceding Probe Color. However, no such interaction was found, $F(1, 14) = 1.8$, $p = .207$, $\eta_p^2 = .11$, and there was also no three-way interaction involving the additional factor Probe Number, $F(7, 98) = 1.2$, $p = .294$, $\eta_p^2 = .08$. The same results were obtained when only probes that produced reliable N2pcs (Probes 3–7) were included in the analysis (Laterality × Preceding Probe Color: $F(1, 14) < 1$, $p = .638$, $\eta_p^2 = .02$; three-way interaction: $F(4, 56) < 1$, $p = .518$, $\eta_p^2 = .06$). These results show that probe N2pcs were not reliably affected by task-unspecific color adaptation or priming effects.

Effects of Target Color Expectations on Search Template Activation

To assess whether and how target selection and search template activation were affected by target color expectations, target and probe N2pcs in the two-color 80/20 task were computed separately for search displays containing either the frequent or the rare color target and for probe displays with a color singleton in the frequent or rare target color. Figure 6A (left panels) shows ERPs elicited at PO7/8 contralateral and ipsilateral to the side of a frequent versus rare color target in the search display and the corresponding N2pc difference waves (right panel). Both color targets triggered clear N2pcs, but this component was smaller and emerged later for rare color targets.

A repeated-measures ANOVA on target N2pc mean amplitudes with the factors Expectation (frequent or rare color target) and Laterality revealed a main effect of Laterality, $F(1, 14) = 81.7$, $p < .001$, $\eta_p^2 = .85$, and a reliable interaction between Laterality and Expectation, $F(1, 14) = 5.3$, $p = .037$, $\eta_p^2 = .28$. Follow-up t tests showed that an N2pc was reliably present for both types of color targets, both $t(14) \geq 5.5$, $p < .001$, $d \geq 0.37$. However, N2pc amplitudes were attenuated for rare as compared with frequent color targets (-1.1 μV vs. -1.5 μV). The N2pc also emerged later for rare relative to frequent color targets (225 msec vs. 216 msec), but this difference only approached statistical significance, $t_c(14) = 1.9$, $p = .084$, $\eta_p^2 = .20$.

Figure 6B shows contralateral–ipsilateral N2pc difference waveforms illustrating the time course of N2pcs for successive probe displays with a singleton that matched either the frequent (top panel) or rare (bottom panel) target color. These continuous difference waves were generated in the same way as the difference waveforms shown in Figure 4B for the one-color and two-color 50/50 tasks. Similar to these tasks, N2pcs were absent for probes that appeared simultaneously with or shortly after the previous search display, emerged during the preparation for the next search episode, and were maximal immediately before the onset of the search display, for Probe 7. Importantly, this temporal pattern was very similar for probes that matched the frequent versus rare target color, and there were no apparent N2pc amplitude differences between these two types of probes. This is also illustrated in Figure 5 (top panel), which shows mean N2pc amplitudes in the two-color 80/20 task for probes that matched the frequent or rare target color, respectively (light vs. dark green bars).

A repeated-measures ANOVA on probe N2pc mean amplitudes with the factors Expectation (probe matching the frequent or rare target color), Probe Number, and Laterality found a main effect of Laterality, $F(1, 14) = 29.0$, $p < .001$, $\eta_p^2 = .67$, demonstrating that probe N2pcs were reliably elicited. As before, there was an interaction between Laterality and Probe Number, $F(7, 98) = 5.6$, $p < .001$, $\eta_p^2 = .29$, reflecting the fact that probe N2pc amplitudes differed between early and later probes within a trial. Critically, there was no interaction between Laterality and Expectation, $F(1, 14) = 0.5$, $p = .492$, $\eta_p^2 = .03$, and also no three-way interaction, $F(1, 14) = 0.9$, $p = .523$, $\eta_p^2 = .06$, demonstrating there were no differences between the amplitudes and time course of N2pcs to probes that matched the frequent or rare target color. Further support for this conclusion was provided by the corresponding Bayes factors for these interactions, $BF_{01} = 4.3$ and 9.7, respectively, for the two- and three-way interaction.

To confirm the absence of any probe N2pc differences associated with target color expectation and to assess when during the preparation period probe N2pcs emerged, follow-up ANOVAs with the factors Expectation and Laterality were conducted separately for each probe (Probes 1 to S). Probes 1–4 and Probe S did not trigger reliable N2pc components, as indicated by the absence of an effect of Laterality, all $F(1, 14) \leq 2.7$, $p \geq .123$, $\eta_p^2 \leq .16$. In contrast, reliable N2pcs were elicited for Probes 5–7, all $F(1, 14) \geq 11.3$, $p \leq .005$, $\eta_p^2 \geq .45$. No interactions between Expectation and Laterality were present for these three probes, all $F(1, 14) \leq 1.6$, $p \geq .229$, $\eta_p^2 \leq .10$, confirming that these probes triggered N2pcs of similar size regardless of whether they matched the frequent or rare target color.

To further assess the effects of probabilistic target color expectations on search template activation, we conducted another analysis that combined the probe N2pc data from the two-color 80/20 and 50/50 tasks, with expectation now a three-level factor (probe matching the target color expected on 80%, 50%, or 20% of all

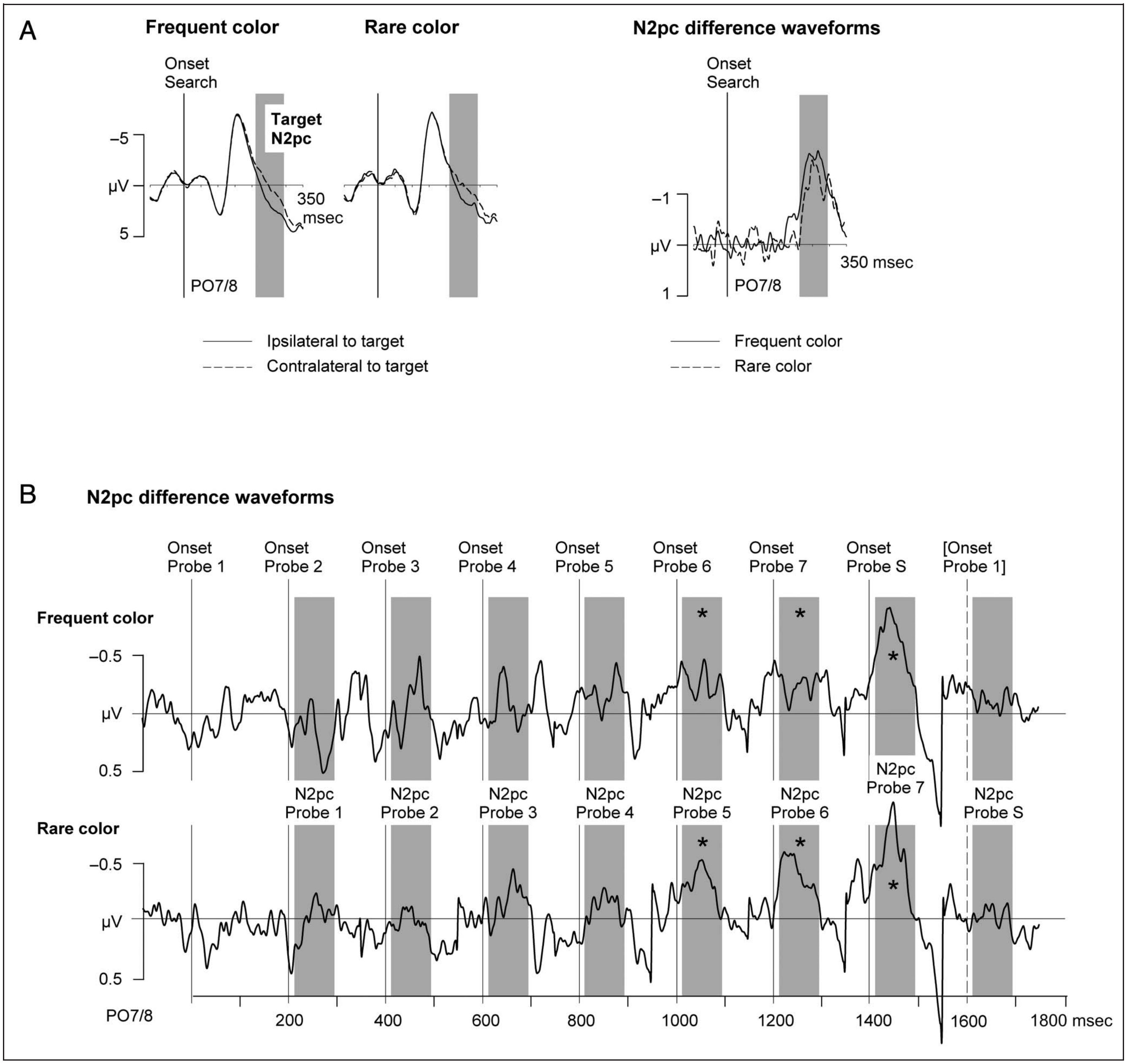

Figure 6. N2pc results obtained in the two-color 80/20 task of Experiment 1. (A) Grand-averaged ERPs elicited by search displays containing a target in the frequent color or in the rare color at electrodes PO7/8 contralateral and ipsilateral to the target (left), together with the corresponding contralateral–ipsilateral N2pc difference waveforms (right). (B) N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for each probe, shown separately for probes that matched the frequent (top) or rare target color (bottom). Difference waves are shown in the same continuous fashion as in Figure 4B, with asterisks marking the presence of significant probe N2pcs. In all panels, shaded areas indicate N2pc time windows (210–290 msec after probe or search display onset).

trials). For this analysis, only probes that produced reliable N2pcs in the two-color 80/20 task (Probes 5–7) were included. There was a main effect of Laterality, $F(1, 14) = 40.0$, $p < .001$, $\eta_p^2 = .74$, and an interaction between Laterality and Probe Number, $F(2, 28) = 5.4$, $p = .011$, $\eta_p^2 = .28$, reflecting the fact that probe N2pc were largest for Probe 7. Critically, there was no interaction between Laterality and Expectation, $F(2, 28) < 1$, $\eta_p^2 = .05$, and also no three-way interaction between Laterality, Expectation, and Probe Number, $F(4, 56) < 1.3$, $p = .283$, $\eta_p^2 = .09$, demonstrating color template activation was not sensitive to differences in expectations regarding the color of search targets.

EXPERIMENT 2

The probe N2pc results from Experiment 1 suggest that two target color templates can be activated simultaneously, without apparent cost relative to single-template activation. Critically, these template activation processes seem to be entirely insensitive to probabilistic expectations about the color of upcoming targets. Before accepting these conclusions and discussing their implications, an alternative interpretation of the findings of Experiment 1 needs to be ruled out. The critical object in all probe displays was a color singleton, which might have captured attention in an entirely exogenous salience-driven fashion, independently of any color-selective search preparation. If this was the case, this would explain the absence of probe N2pc differences between one-color and two-color search and the absence of any effects of probabilistic expectations on these N2pcs during two-color search. This type of attentional capture could be linked to increased arousal levels during the period just before the arrival of the next search display, which would explain why probe N2pcs only emerge during the later part of the preparation period. This alternative account in terms of exogenous attentional capture is not in line with the results of our previous study (Grubert & Eimer, 2018), where both target color and nontarget color singleton probes were employed. Even though these probes were equally salient, N2pcs were exclusively triggered by target color probes but were absent for nontarget color probes. However, as participants always searched for a single constant color target in this prior study, it remains possible that probe N2pcs are color selective only under these conditions but salience driven in search tasks where the color of the next target is not predictable.

Experiment 2 was run to test this possibility. Procedures were similar to the two-color 50/50 task of Experiment 1, except that each probe display was now equally likely to contain a singleton with one of four different colors: the two possible target colors and two new distractor colors. We included two different distractor colors to make all template-matching and nonmatching probes equiprobable. In contrast to Experiment 1, where the two target colors remained constant for each participant, these colors were selected randomly from a set of three colors for each block in Experiment 2. This was done to test whether probe N2pcs remain color selective during two-color search when target color assignments change frequently. If there was salience-driven attentional capture by color singleton probes during two-color search in Experiment 2, reliable N2pc components should be observed not only for target color but also for distractor color probes. If these probe N2pcs were exclusively due to exogenous attentional capture, they should be identical for both types of probes. Alternatively, if these probe N2pcs are a valid marker of color-selective template activation processes during two-color search, they should only be triggered by target color probes but not by distractor color probes.

Methods

Participants

Eighteen new participants were paid to take part in Experiment 2. Three participants were excluded from analysis because they lost more than 40% of all data during artifact rejection because of eye movements. The remaining 15 participants were aged between 20 and 52 years (mean = 33.1 years, *SD* = 10.5 years). Eleven were female, and all participants were right-handed. All had normal or corrected-to-normal vision and no color vision deficiencies (as tested with the Ishihara color vision test; Ishihara, 1972).

Stimuli, Procedures, and EEG Parameters

Stimuli and procedures were the same as in the two-color 50/50 task of Experiment 1, with the following exceptions. Probe displays now contained color singletons that either matched one of the two possible target colors or one of two possible distractor colors. Target and distractor colors for each block were selected randomly from sets of primary (red, green, blue) and mixed colors (pink, yellow, cyan), respectively, to ensure separability in color space of the target colors (color coordinates and luminance were the same as in Experiment 1). For eight participants, target colors were drawn from the set of primary colors and distractor colors from the set of mixed colors, and vice versa for the other seven participants. For each of the eight probe displays on each trial, one of the four possible target and distractor colors was chosen randomly as the color singleton. The search displays were the same as in the two-color 50/50 task of Experiment 1. Each search display contained one target color bar (randomly presented but equiprobably matching one or the other target color of each block), two bars matching the two distractor colors of each block, and three nontargets—one in gray and two more in the remaining colors of each color set. Experiment 2 contained 30 blocks of 12 trials. Probe N2pcs were computed separately for target color and distractor color probes (collapsed across the two target and distractor colors, respectively). EEG recording, artifact rejection, and data analysis parameters were identical to Experiment 1. During artifact rejection in Experiment 2, 8.4% (*SD* = 7.3%) of all epochs (ranging between 0.4% and 20.4% across participants) were excluded from analysis. N2pc components were analyzed in the same 210–290 msec time window used in Experiment 1.

Results

Behavioral Results

Less than 0.1% of all trials were excluded as anticipatory (<200 msec) or very slow (>1500 msec) responses. Mean correct RT was 680 msec, and participants made 4.7% errors.

N2pc Components

Target objects in the search display (as shown in Figure 7A) triggered a reliable N2pc, $t(14) = 4.8$, $p < .001$, $d \geq 0.25$, with an estimated onset of 248 msec

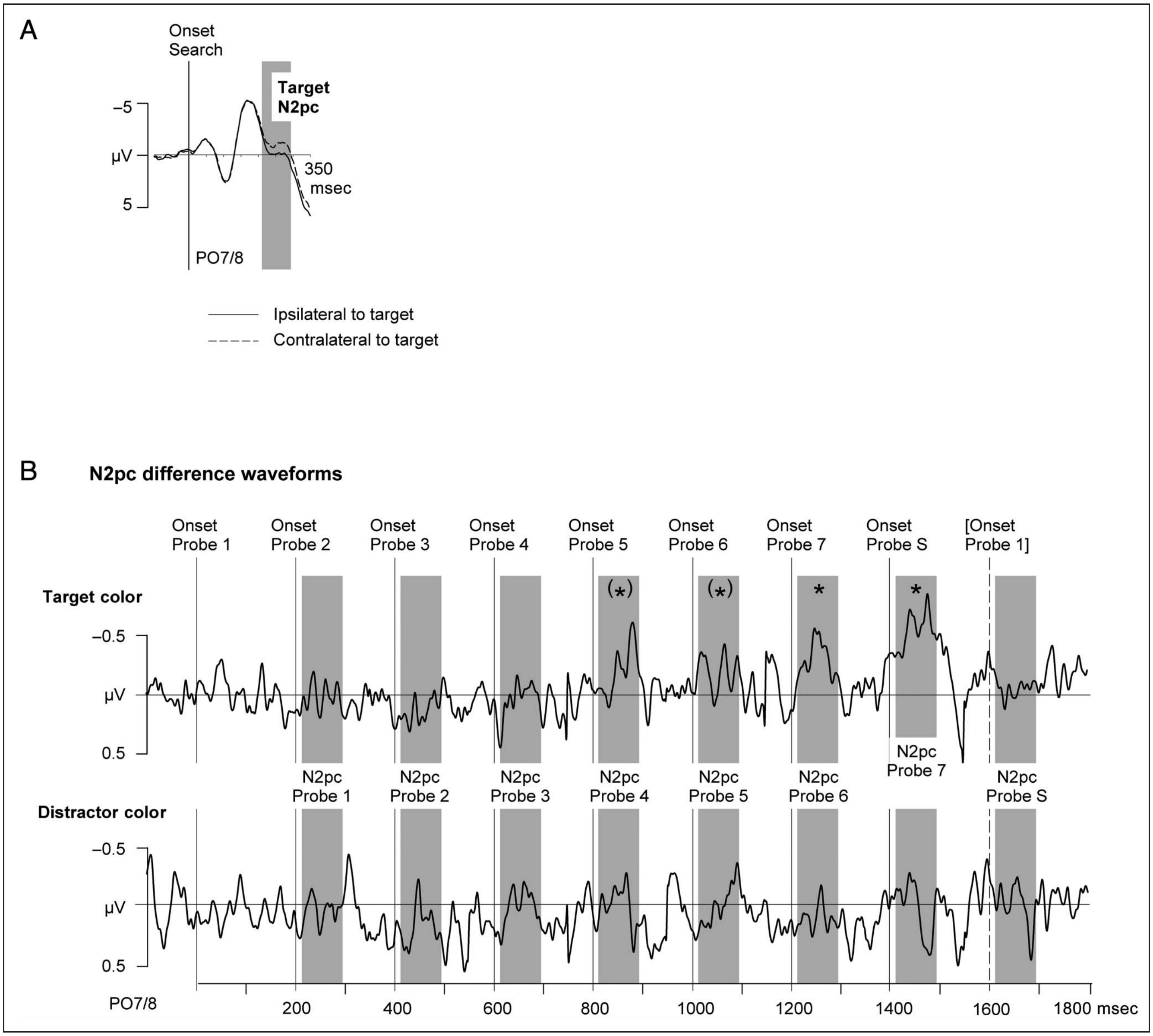

Figure 7. N2pc results obtained in Experiment 2. (A) Grand-averaged ERPs elicited at electrodes PO7/8 contralateral and ipsilateral to the target in the search displays. (B) N2pc difference waves obtained by subtracting ipsilateral from contralateral ERPs for each probe, shown separately for target color (top) and distractor color probes (bottom). Probe N2pcs are shown in the same continuous fashion as in Figures 4B and 5B. Asterisks indicate significant and marginally significant (in brackets) probe N2pcs. Shaded areas mark N2pc time windows (210–290 msec after probe or search display onset).

poststimulus (jackknifed latency at 50% of the peak amplitude). N2pc components to target color and distractor color probes are shown in Figure 7B. The continuous difference waves shown here are analogous to the probe N2pc difference waveforms shown in Figures 4B and 6B for Experiment 1. The corresponding probe N2pc mean amplitude values are shown in Figure 5 (bottom panel), separately for target color and distractor color probes, respectively.

A repeated-measures ANOVA with the factors Probe Color (target color, distractor color), Probe Number (Probes 1–7, Probe S), and Laterality (electrode ipsilateral, contralateral to the side of the probe) compared N2pc mean amplitudes triggered in response to target versus distractor color probes for each of the eight probes presented within a trial. There was no main effect of Laterality, $F(1, 14) < 1$, $\eta_p^2 = .04$. However, importantly, there was a significant interaction between Probe Color and Laterality, $F(1, 14) = 5.0, p = .042$, $\eta_p^2 = .26$, indicating that target and distractor color probes elicited different N2pc activation patterns across all probes. This interaction was followed up by two separate ANOVAs for each probe color. The ANOVA for target color probes showed a main effect of Laterality, $F(7, 98) = 9.0, p = .010$, $\eta_p^2 = .39$, and an interaction between Probe Number and Laterality, $F(1, 14) = 4.8, p < .001$, $\eta_p^2 = .25$, indicating that probe N2pcs were reliably present and differed as a function of the temporal position of the probes. Follow-up t tests confirmed that

Probes 6 and 7 elicited reliable N2pc components, both $t(14) > 2.5, p < .021, d > 0.29$. Probes 4 and 5 triggered marginally significant N2pcs, both $t(14) > 2.0, p < .071, d > 0.14$. In marked contrast, the ANOVA for distractor color probes did not produce a main effect of Laterality, $F(1, 14) = 0.8, p = .399, \eta_p^2 = .05, \mathrm{BF}_{01} = 3.1$, and also no interaction between Laterality and Probe Number, $F(7, 98) = 0.3, p = .965, \eta_p^2 = .02, \mathrm{BF}_{01} = 40.6$. This suggests that there was no exogenous attentional capture by any of the distractor color probes. Follow-up analyses showed that none of these probes elicited reliable N2pcs, all $t(14) < 1.5, p > .194, d < 0.05$.

DISCUSSION

During visual search, attentional templates represent features that are relevant for the selection of target objects. Such templates are activated in a transient fashion during the preparation for an upcoming search episode, and the time course of these activation processes can be regulated in line with the predicted onset of the next search display (Grubert & Eimer, 2018). Here, we investigated template activation processes during two-color search, where two preparatory color templates should be activated simultaneously. Our central goal was to find out whether these processes are sensitive to probabilistic expectations about the likely identity of the next color-defined search target. To assess this, we measured N2pc components to brief color singleton probes that appeared every 200 msec during the interval between successive search displays. Probes that match a current target color should capture attention when a corresponding search template is activated and should therefore trigger N2pc components.

First, we confirmed that two color-specific search templates can be activated in parallel. In Experiment 1, probe N2pcs were measured in a two-color 50/50 task where both color-defined targets were equally likely to appear in any search display and in a one-color task where search targets were defined by a single constant color. The temporal pattern of probe N2pcs observed in the one-color task confirmed the results of our previous study that employed analogous RSPP procedures (Grubert & Eimer, 2018). Reliable probe N2pcs were elicited from Probe 3 onward but were absent for earlier probes, indicating that target templates were activated anew on each trial, approximately 1000 msec before the onset of the next search display. Essentially the same temporal pattern of probe N2pc components was observed in the two-color 50/50 task. Importantly, there were no probe N2pc amplitude differences between the two tasks, as also confirmed by a Bayesian analyses that provided substantial evidence for the null hypothesis. Follow-up analyses for the two-color 50/50 task showed that there were no differential effects of color priming or adaptation between same-color probes in successive probe displays. These observations confirm and extend previous evidence that two color-specific search templates can be activated in parallel (e.g., Beck et al., 2012; Irons et al., 2012; Moore & Weissman, 2010). They also suggest that there are no obvious costs resulting from competitive interactions between two templates that are simultaneously active during search preparation.

The central new result of this study was that these template activation processes are remarkably insensitive to probabilistic expectations about upcoming target objects. This was evident in the two-color 80/20 task of Experiment 1, where one color target appeared in 80% of all search displays and the other in only 20%. If the activation states of the corresponding search templates had been adjusted in a predictive fashion in line with these target probabilities, N2pcs to probes matching the frequent target color should have been larger in size and possibly emerge earlier during preparation for search than N2pcs to probes that matched the rare target color. In fact, no such differences in the amplitudes and the time course of N2pcs elicited by these two types of probes were found. There were also no expectation-related differences between probe N2pcs when data from the two-color 80/20 and 50/50 tasks were analyzed together. These observations suggest that search templates for likely, unlikely, and equiprobable target colors were activated to the same degree, and this conclusion was also supported by the corresponding Bayes factors ($\mathrm{BF}_{01} > 3$ in all cases). Our previous study (Grubert & Eimer, 2018) has shown that the activation of attentional templates can be flexibly adjusted to the predictable onset of search displays, demonstrating that the top–down control of search templates is tuned to temporal predictions. The current results indicate that this sensitivity to expectations may be specific to the time domain, but that search template activation processes are not sensitive to expectations about the likely identity of search target objects. However, it should be noted that the absence of any expectation effects on color-specific preparation processes in this study may be linked to the fact that there were only two possible color-defined targets, which can be maintained simultaneously in working memory. In situations where the number of alternative target colors matches or exceeds working memory capacity, additional information about target probabilities might be still used to prioritize search templates for more likely colors to optimize task performance. This possibility will need to be investigated in future research.

To rule out the possibility that instead of reflecting the activation of preparatory target color templates, the probe N2pcs in the two-color tasks of Experiment 1 were the result of salience-driven attentional capture by all singleton probes, we ran another two-color 50/50 task in Experiment 2, which included distractor color probes. N2pc components were only triggered by target color probes but were entirely absent in responses to distractor color probes, in spite of the fact that both types of probe singletons were equally salient. This observation confirms that the probe N2pcs observed in Experiment 1 were indeed linked to the activation of search templates. Thus, they do not reflect task-unrelated bottom–up attentional capture effects that might have been associated with increased arousal levels toward the end of a preparation period.

The apparent absence of any costs for template activation processes during two-color as compared with single-color search and the insensitivity of these processes to probabilistic expectations, as revealed by the probe N2pc results in Experiment 1, contrast remarkably with the behavioral and N2pc results observed in response to search target displays. For these displays, there were clear performance costs in the two-color 50/50 task relative to the one-color task, and target N2pc components were delayed and reduced in amplitude. This is in line with previous studies, which have also found behavioral and electrophysiological costs and for the selection of targets during two-color relative to one-color search (e.g., Kerzel & Witzel, 2019; Grubert & Eimer, 2013, 2015, 2016; Irons et al., 2012; Dombrowe, Donk, & Olivers, 2011; see Ort & Olivers, 2020, for a review). The current results suggest that these two-template costs arise exclusively at the stage where target objects are selected and not during the preceding search preparation stage (see also Ort, Fahrenfort, ten Cate, Eimer, & Olivers, 2019, for further evidence for a distinctive bottleneck of multiple-target search at the level of target selection). Along similar lines, there were also clear effects of probabilistic target color expectations on target selection and manual responses to search displays. In the two-color 80/20 task of Experiment 1, RTs to targets were slower for rare as compared with frequent color targets, and N2pcs elicited by rare targets were smaller and tended to be delayed (see also Berggren & Eimer, 2019, for corresponding results).

These clear dissociations between preparatory search template activation processes and processes that operate during the selection of target objects are remarkable, but their basis remains to be discovered. It is clear that the activation of color-specific templates was task relevant in the current experiments. Because search targets always appeared together with distractors in different nontarget colors, these templates were essential to guide attention rapidly to target objects. However, it is possible that they were exclusively involved in the guidance of search, but not in subsequent target selection processes. Such a distinction between "guiding" and "target" templates was recently proposed by Wolfe (2021) in his latest version of the Guided Search model. In Guided Search 6.0, guiding templates are representations of target-defining features that can be activated during search preparation and guide attention to potential target objects. Target templates are required once attention has been allocated to an object to decide whether this object is actually a target and/or to identify this object and its associated response. Although this distinction is most relevant for hybrid search/memory tasks (e.g., search for any of n possible targets within a given category [e.g., Schneider & Shiffrin, 1977]), it may also apply to more standard search tasks where targets are defined by one visual attribute (e.g., color) and response selection is determined by a different attribute of the same object (e.g., orientation). In such tasks, guidance templates may be entirely feature-based (e.g., templates for red or green objects), whereas target templates could represent integrated objects (e.g., templates for red or green and horizontal or vertical target bars).

Within such a framework, the current results suggest that two guidance templates can be concurrently active without apparent costs during search preparation, whereas there is strong competition between two simultaneously activated target templates. This competition impairs the ability of either of these templates to control the identification of attended target objects, resulting in the performance and electrophysiological costs observed during two-color as compared with one-color search (see also Ort et al., 2019, for evidence that such multiple-feature costs primarily affect target selection rather than search preparation). With regard to probabilistic expectations, there is evidence from an fMRI study (Jiang, Summerfield, & Egner, 2016) that probability-based predictions primarily operate at the level of objects rather than individual features. If this is the case, such predictions should only affect object-based target templates but not feature-based guidance templates. This would explain why there was no bias favoring the preparatory activation of guidance templates for expected colors, though such a bias was clearly present during target identification, as reflected by the effects of probabilistic expectations in the two-color 80/20 task on RTs to search targets and on the amplitude and latency of N2pc components triggered by these targets.

In summary, this study obtained new electrophysiological evidence for multiple-template activation during the preparation for visual search. Most importantly, it also showed that, in marked contrast to target selection processes, preparatory search template activation appears to be entirely insensitive to probabilistic expectations about upcoming target objects. The mechanisms responsible for this notable dissociation between expectation effects on search preparation and target selection will need to be investigated more systematically in future work.

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Data Availability Statement

The data supporting the findings of this study are available upon request.

Author Contributions

Anna Grubert: Conceptualization; Data acquisition; Data analysis; Data interpretation; Manuscript preparation;

Operationalization. Martin Eimer: Conceptualization; Data interpretation; Manuscript preparation; Operationalization.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .407, W(oman)/M = .32, M/W = .115, and W/W = .159, the comparable proportions for the articles that these authorship teams cited were M/M = .549, W/M = .257, M/W = .109, and W/W = .085 (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

Notes

1. Electrodes PO7/8 are standard sites for N2pc experiments, as N2pc amplitudes are typically maximal at this site relative to adjacent lateral posterior electrodes. To confirm this and to show that the choice of these specific sites did not affect the probe N2pc results, we ran an additional analysis of probe N2pc mean amplitudes for the one-color versus two-color 50/50 tasks in Experiment 1 that included the factor Electrode Site (PO7/8, P3/4, and P7/8). There was an interaction between Electrode Site and Laterality, $F(2, 28) = 22.5, p < .001, \eta_p^2 = .62$, because of the fact that probe N2pcs were largest at PO7/8. There were no significant higher-order interactions including the factor Electrode Site.
2. Because there were no differences between N2pc components triggered by color singleton probes matching either of the two equiprobable target colors in the two-color 50/50 task, ERPs were pooled across both color probes. There were also no significant differences between N2pcs and probes that matched or did not match the color of the search target on the preceding trial (i.e., no target-probe intertrial priming effects).
3. We thank an anonymous reviewer for raising our awareness of the alpha inflation in multicomparison ANOVAs including factors of more than two levels (Cramer et al., 2016). All interactions of such omnibus ANOVAs reported in this publication would have survived Bonferroni correction, if applied, apart from this three-way interaction. However, since this interaction was not in line with the general pattern observed (i.e., no difference between one- and two-color search), confirmatory follow-up analyses were still conducted to rule out any potential effects of theoretical importance.
4. N2pcs to probes at different temporal positions are independent; because they were triggered at different points in time during the interval between two search displays, no Bonferroni correction was applied to these and subsequently reported analogous t tests.

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