The Roles of Relevance and Expectation for the Control of Attention in Visual Search

Nick Berggren and Martin Eimer
Birkbeck University of London

Representations of target-defining features (attentional templates) control the allocation of attention during visual search. We investigated whether template-guided attentional selectivity is sensitive not only to the relevance of visual features, but also to expectations about their probability. Search displays could contain a target in an expected (80%) or unexpected (20%) color. They were preceded by spatially uninformative cues that matched either the expected or unexpected target color. These color cues attracted attention, reflected by behavioral spatial cueing effects and by cue-elicited N2pc components obtained via EEG measured during task performance. Critically, these attentional capture effects were identical for both color cues, suggesting that preparatory attentional templates only reflect relevance, and are insensitive to expectations about target color probabilities. In contrast, RTs and N2pc components to search targets in the unexpected color were delayed, showing that expectations modulated the speed of attentional target selection within search displays. This dissociation between the effects of relevance and expectation on attentional preparation versus target selection suggests that these 2 parameters for attentional control are represented differently. Task relevance is likely to be specified at the level of individual features, whereas expectations could be represented in an object-based fashion.

Public Significance Statement
Visual search for a target object among distractors (e.g., an apple in a fruit bowl) is controlled both by our knowledge about the relevance of specific target features (e.g., the apple can be red or green) and by our expectations (e.g., the apple is likely to be red). This study shows that these two factors operate differently. Relevant features are represented equally, regardless of expectations, when we prepare for search, but our ability to direct attention to a search target may be facilitated by object-based expectations.

Keywords: selective attention, top-down control, visual expectancy, feature-based attention, event-related brain potentials

During visual search, representations of known target features (attentional templates) can be utilized to guide attention toward possible target objects (Duncan & Humphreys, 1992). Research employing spatial cueing procedures has shown that such templates are activated in a preparatory fashion, prior to the presentation of actual search displays. When such displays are preceded by spatially uninformative cues that match a target attribute (e.g., color, size), reaction times (RTs) are faster when a subsequent search target appears at the same location as a cue relative to

targets at other uncued locations, indicating that target-matching cues attracted attention (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992). Crucially, cues that do not match the target-defining feature do not capture attention, as reflected by the absence of spatial cueing effects (Folk et al., 1992; see also Eimer & Kiss, 2008, for corresponding electrophysiological evidence).

There has recently been substantial debate about whether multiple preparatory attentional templates for different target features can be activated in parallel. Such templates are believed to be held within visual working memory, based on findings that search-unrelated items stored in working memory can bias attention toward memory-matching stimuli in visual search tasks (see, e.g., Soto, Hodsoll, Rotshtein, & Humphreys, 2008), and that visual working memory load can impair feature-guided attentional selection (e.g., Berggren & Eimer, 2018; Woodman, Luck, & Schall, 2007). Because visual working memory has a typical capacity of around 3–4 items (e.g., Luck & Vogel, 1997), one might expect that observers can store multiple attentional templates simultaneously. However, it has been argued that only a single working memory representation can be prioritized as a search template at

any given time, with other concurrently held working memory items unable to guide attentional selectivity (Olivers, Peters, Houtkamp, & Roelfsema, 2011). Recent spatial cueing experiments have provided evidence against this single-template hypothesis. For example, Irons, Folk, and Remington (2012) employed a two-color search task where targets could appear in one of two equally likely colors, and found spatial cueing effects indicative of attentional capture for cues that matched either of these target colors, but not for other target-nonmatching color cues. This suggests that attentional templates for different colors can be activated concurrently (see also Adamo, Pun, Pratt, & Ferber, 2008; Beck, Hollingworth, & Luck, 2012; Moore & Weissman, 2010, for similar conclusions).

Additional electrophysiological evidence for multiple parallel color templates was provided by Grubert and Eimer (2016), who employed procedures analogous to the two-color search tasks by Irons et al. (2012), and confirmed the presence of behavioral spatial cueing effects for both target-matching cues but not for cues in nonmatching colors. In this study, event-related potentials (ERPs) were recorded to measure N2pc components elicited by target-color matching and nonmatching cue stimuli. The N2pc is an enhanced negativity triggered during visual search tasks over posterior scalp electrodes contralateral to the visual hemifield where a stimulus with target-matching attributes is presented, typically emerges at around 180–200 ms poststimulus onset, and is interpreted as a marker of the allocation of attention to task-relevant stimuli (e.g., Eimer, 1996; Luck & Hillyard, 1994). By measuring N2pcs to target-matching and nonmatching cues that appear prior to the presentation of a search display, these components can also be used to measure the activation states of attentional templates for target-defining features (e.g., Eimer & Kiss, 2008; Grubert & Eimer, 2018). During two-color search, only target-matching cues elicited N2pc components, which were similar in size to the N2pcs measured in a single-color task where all targets were defined by the same color (Grubert & Eimer, 2016). In contrast, no N2pc was triggered by nonmatching cues. These observations provide online ERP evidence for the hypothesis that multiple color templates can be activated in parallel during the preparation for search, prior to the arrival of search displays.

If multiple feature templates for target-defining features can be maintained simultaneously, the important question arises whether the activation states of these templates are fixed (either "on" or "off") or whether they can be regulated in an adaptive fashion. It is clear that attentional templates represent visual attributes that are currently task-relevant, but these templates may also be sensitive to other top-down factors. For example, it is widely believed that expectations about the probability of anticipated features, objects, and events can modulate visual selectivity (e.g., Feldman & Friston, 2010; Summerfield & de Lange, 2014). The question whether relevance and expectation have similar or qualitatively different effects on the selectivity of visual processing remains controversial. A standard view is that knowledge about the relevance of specific visual attributes improves perceptual sensitivity, while information about their probability primarily affects post-perceptual decision and response selection mechanisms (e.g., Kinchla, 1992). However, there is also evidence that in the case of spatial attention, both factors may affect early sensory-perceptual stages of visual

processing (e.g., Wyart, Nobre, & Summerfield, 2012). It is as yet unknown whether in addition to relevance, expectation can also affect the activation states of preparatory attentional templates for target-defining features during visual search. This was investigated in the present study.

In the context of visual search tasks, relevance refers to those visual features that distinguish target and nontarget objects, while expectation is determined by the probability that particular features will occur during a particular search episode. Here, we assessed the impact of expectation about the probability of target-defining features on template activation processes with two-color search tasks similar to those employed by Irons et al. (2012), by manipulating the likelihood that one of two possible color-defined targets would appear in a search display. Participants searched for rectangular color-defined target bars among distractor bars in different nontarget colors, in order to report the orientation of the target (horizontal or vertical). Targets could have one of two possible colors (i.e., both colors were equally task-relevant), and the probability that a search display would contain either of these targets was manipulated. In Experiment 1, the two color targets were either equiprobable (50–50 task), or one of these two targets was presented in 80% of all search displays and the other color target in the remaining 20% (80–20 task). In both tasks, search displays were preceded by task-irrelevant cue displays that contained a color singleton item that matched one of the two target-defining colors (see Figure 1). Each cue display was equally likely to contain either of these two colors, and the location of these color cues was spatially uninformative with respect to the location of the subsequent search target. To assess the activation of color-specific attentional templates, behavioral spatial cueing effects were measured as markers of task-set contingent attentional
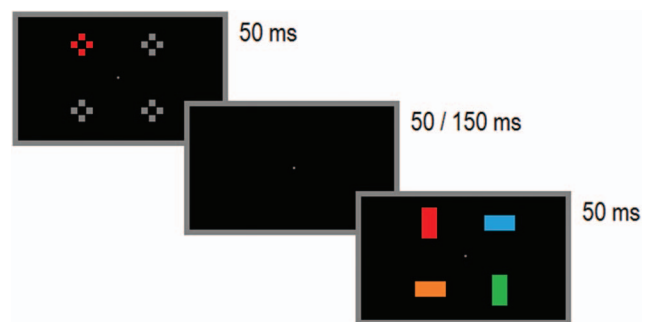
Figure 1. Example sequence of displays on a single trial in Experiments 1 and 2 (not to scale). Spatially uninformative cue displays were followed after an interval of 50 ms (Experiment 1) or 150 ms (Experiment 2) by search displays. Search displays contained a rectangular target bar in one of two possible target colors among three distractor bars in three different colors. Participants reported the orientation of the search target object (horizontal/vertical). Cue displays included a color singleton object that matched one of the two target colors. The locations of the color cues and the subsequent search target were uncorrelated. In the 80–20 tasks of Experiments 1 and 2, the search target had one color in 80% of all trials and the other color in 20% of trials. In the 50–50 task of Experiment 1, both target color objects were equally likely. Cue displays were equally likely to include either target-matching color in both experiments. See the online article for the color version of this figure.

capture by each of the two color cues, separately for the 50–50 and 80–20 tasks.

In the 50–50 task, where both target colors were equally expected, reliable spatial cueing effects of equal size should be triggered by both color cues, demonstrating that these cues attracted attention, in line with the hypothesis that two color templates can be activated in parallel (see also Grubert & Eimer, 2016; Irons et al., 2012). The critical new question concerned the pattern of spatial cueing effects obtained in the 80–20 task, where the two possible cue colors were both relevant, but matched either the target that was more likely or less likely to appear in the upcoming search display. If the activation states of attentional templates can be flexibly adjusted in line with expectations about target probabilities, color cues that match the more likely target color should capture attention more strongly than cues in the other less likely target color. As a result, significantly larger spatial cueing effects should be found for cues in the expected target color. Alternatively, search templates may only adopt binary states ("on"/"off") that are determined exclusively by relevance, and may be entirely insensitive to expectation. In this case, equivalent spatial cueing effects should be observed for both color cues in the 80–20 task, suggesting the ability of these cues to attract attention was unaffected by expectations about target colors. This would indicate that template states cannot be adjusted to reflect the probability that one of these templates will be involved in an upcoming target selection episode.

In addition to measuring spatial cueing effects, we also compared RTs to search targets in the 80–20 task for search displays that contained the expected versus unexpected target color. Classic psychometric research has demonstrated robust effects of expectation (i.e., target stimulus probabilities) on response speed, with faster RTs in response to more frequent stimuli (e.g., Fitts, Peterson, & Wolpe, 1963; Hyman, 1953; see Smith, 1968, for review), which remain present when effects on response probability are controlled for (LaBerge & Tweedy, 1964). Analogous expectation-related effects (i.e., faster responses for targets in the high-probability color) should also be observed in the 80–20 task of Experiment 1.

Experiment 1

Method

Participants. Thirteen participants were recruited to participate in Experiment 1. Data from one participant was excluded and replaced due to atypical extreme negative spatial cueing (strongly delayed RTs for targets at cued locations) within the baseline 50–50 task. The remaining sample of 12 participants (*M* age = 26 years, *SD* = 7, 8 male; 1 left-handed) all reported normal or corrected-to-normal vision and were naïve to the experimental hypotheses. Sample size was defined based on pilot data (*N* = 12) from an experiment that used the same stimulus setup and procedures as the 50–50 task of Experiment 1. Participants searched for one of two equally likely target colors, and cue displays could contain a color singleton matching these target colors, or two possible nontarget colors. Spatial cueing effects were measured separately for target-color and nontarget-color cues. Results replicated the standard finding that only target-color cues triggered spatial cueing effects of 21 ms (*SD* = 19), while nontarget color

cues produced a tendency toward inverse cueing effects (−12 ms; *SD* = 22), providing a general effect size for differences in task-contingent spatial cueing (*dz* = 1.07). Analysis using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007) assuming an alpha level of .05 and power of .80 gave a recommended minimum sample size of 9 participants. We therefore retained the same sample size as in our pilot experiment, which was sufficiently well-powered.

Stimuli and procedure. The experimental task was created and run using E-Prime 2.0 software (Psychology Software Tools, Inc.). Stimuli were presented on a 24-in. BenQ monitor (60 Hz, 1920 × 1080 screen resolution) at a viewing distance of approximately 90 cm. The experiment was run on a SilverStone PC, with manual responses registered via keyboard button response. Stimuli were presented on a black background with a gray fixation cross (0.25 × 0.25 degrees of visual angle) present throughout blocks. Cue displays contained four "clusters" of small squares at four quadrants from fixation. Each square measured 0.16 × 0.16°, with each cluster measuring 0.64 × 0.64°. The eccentricity measured from the center of each cluster to center of fixation was 1.66°. Of the four cue clusters on each trial, one consisted of colored squares, while the other three consisted of gray squares. Search displays contained four differently colored rectangular bars (0.51 × 1.15°) at the same eccentricities as cue clusters. On each trial, two bars were presented in horizontal orientation and two vertical. The colors used in the experiment were red (CIE coordinates: .605/.322), orange (.543/.409), green (.296/.604), blue (.169/.152), magenta (.270/.134), and gray (.305/.325). Gray items only appeared in the cue displays. All colors were equiluminant (14 cd/m²).

Trials began with a cue display (50 ms duration), which was followed after a 50 ms interstimulus interval by a search display (50 ms duration). The interval between the offset of the search display and the onset of the cue display on the next trial was 1950 ms. On each trial, participants had to find the rectangular target bar in the search display that matched one of two possible target colors, and to report whether this bar was horizontally or vertically oriented by pressing the "0" or "2" key with their right index or middle finger respectively on the numeric keypad. Responses were registered within a 1500-ms interval after the onset of each search display.

Two blocked task conditions were run, with task order counterbalanced between participants. In the *50–50 task*, two possible target colors were defined at the start of the first block, and remained constant for 8 experimental blocks of 32 trials each. Here, search displays were equally likely to contain a target bar in either of the two target colors. Cue displays were also equally likely to contain either target-defining color. The assignment of the cue and target colors on each trial was independent, so that the cue and target colors were identical on half of all trials and different on the other half. Color cues and targets were equally likely to occur at any of the four possible locations in the cue and target displays, respectively. Their locations were selected independently on each trial, so that color cues were spatially uninformative regarding the location of the upcoming target object. Cues and targets appeared at the same location on 25% of all trials, and at different locations on 75%. The *80–20 task* was identical to the 50/50 task, except that target objects in one color appeared on the majority of all

trials (80%), and targets in the other color on the remaining 20%. Cue displays were again equally likely to contain either target color. Participants were explicitly told that the target bars were "much more likely" to have one specific color, but that the other target color would also appear on a minority of trials. Participants completed 12 experimental blocks of 40 trials each in the 80/20 task.

In both tasks, target colors were chosen from four possible colors (red, blue, green, and magenta), with two colors for the 50–50 task and two different colors for the 80–20 task. The assignment of target colors to the two tasks, and the choice of the more/less frequent target color in the 80/20 task, were counterbalanced across participants. They were informed by the experimenter about the two target-defining colors prior to the first block of each task, and these colors were also specified on an instruction screen that was shown at the start of each block. Participants completed a short practice block before each of the two tasks. In both tasks, the factors color cue location (four locations), color cue identity (two colors), target location (four locations), and target color identity (two colors) were determined independently for each trial, with the stipulation that an equal number of trials be presented for each value of these factors across all blocks of each task (apart from target color identity in the 80–20 task, which was weighted 4:1 in favor of the more probable target color).

Results

50–50 task. Mean RTs and error rates on valid and invalid trials are shown in Table 1 (top panel), separately for trials with either of the two equiprobable cue and target colors (Color 1, Color 2, randomly determined for each participant). For RTs, a $2 \times 2 \times 2$ repeated-measures Analysis of Variance (ANOVA) was run for trials with correct responses, with the factors Cue Color (Color 1, Color 2), Target Color (Color 1, Color 2), and Cue Validity (target at cued vs. uncued location). Analysis showed a significant main effect of Cue Validity ($F(1, 11) = 8.60$, $p = .01$, $\eta_p^2 = .44$), showing reliably faster RTs on trials where the target appeared at the same location as the preceding color cue ($M = 616$ vs. 637 ms). There were no main effects of Cue Color or Target Color ($Fs < 1$), but a significant Cue Color $\times$ Target Color interaction was present ($F(1, 11) = 30.67$, $p < .001$, $\eta_p^2 = .74$). RTs were faster on trials where the cue and target colors matched than when they were different ($M = 584$ vs. 669 ms; see Table 1). There were no reliable interactions between Cue Validity and Cue Color ($F < 1$), Target Color, $F(1, 11) = 1.03$, $p = .33$, or as part of a three-way interaction ($F < 1$). A matching analysis of error rates showed a nonsignificant trend for a main effect of Cue Validity ($F(1, 11) = 3.16$, $p = .10$, $\eta_p^2 = .22$), with more errors on trials where targets appeared at uncued versus cued locations ($M = 8$ vs. 5%). There was also a significant Cue Color $\times$ Target Color interaction ($F(1, 11) = 5.97$, $p = .03$, $\eta_p^2 = .35$), as errors were less frequent on trials where cue and target colors were identical than when they differed ($M = 5$ vs. 8%). No other significant main effects or interactions were present ($Fs < 1$).

80–20 task. Mean RTs and error rates for this task are shown in Table 1 (middle panel), separately for trials where cue displays contained an object in the expected (80%) and unexpected (20%) target color. Analogous $2 \times 2 \times 2$ ANOVAs were

Table 1

Mean Reaction Time in Milliseconds (Upper Row) and Error Rate Percentages (Lower Row) in the 50–50 and 80–20 Tasks of Experiments 1, and Main Task of Experiment 2, as a Function of Target Color, Cue Color, and Cue Validity

	Experiment 1 (50–50 Task)			
	Cue in Target color 1		Cue in Target color 2	
Target color	Invalid	Valid	Invalid	Valid
Target color 1	596 (117)	577 (119)	675 (161)	664 (141)
	6 (5)	5 (5)	9 (5)	7 (8)
Target color 2	675 (176)	660 (156)	601 (125)	562 (144)
	10 (10)	6 (9)	6 (5)	4 (5)
	Experiment 1 (80–20 Task)			
	Expected target color cue		Unexpected target color cue	
	Invalid	Valid	Invalid	Valid
Expected target color (80%)	587 (115)	543 (124)	636 (128)	617 (131)
	5 (5)	3 (3)	6 (5)	5 (4)
Unexpected target color (20%)	741 (162)	691 (145)	631 (135)	572 (108)
	10 (7)	11 (12)	5 (5)	5 (5)
	Experiment 2			
	Expected target color cue		Unexpected target color cue	
	Invalid	Valid	Invalid	Valid
Expected target color (80%)	584 (115)	565 (123)	602 (120)	593 (131)
	6 (4)	5 (7)	6 (4)	5 (6)
Unexpected target color (20%)	660 (136)	652 (137)	624 (144)	615 (151)
	8 (9)	5 (5)	7 (8)	7 (13)

Note. Standard deviations are presented in parentheses.

run on RTs and error rates, where the factors Cue Color and Target Color now referred to the expected versus unexpected target color. A significant main effect of Cue Validity ($F(1, 11) = 33.17$, $p < .001$, $\eta_p^2 = .75$) reflected the presence of spatial cueing effects, with faster RTs for targets at cued versus uncued locations ($M = 605$ vs. 649 ms). Critically, there was no interaction between Cue Validity and Cue Color ($F < 1$). Spatial cueing effects of similar magnitude were observed regardless of whether the cue matched the expected (80%) or the unexpected (20%) target color (M diff = 47 vs. 39 ms). There was a nonreliable tendency toward a Target Color $\times$ Cue Validity interaction ($F(1, 11) = 3.24$, $p = .099$, $\eta_p^2 = .23$). Spatial cueing effects were numerically larger on trials with unexpected-color as compared to expected-color targets (M diff = 55 ms vs. 32 ms); however, cueing effects were reliable for both types of trials (both $t(11) > 4.47$, both $p = .001$). Analogous to the 50/50 task, there was a significant interaction between Cue Color and Target Color ($F(1, 11) = 30.71$, $p < .001$, $\eta_p^2 = .74$), reflecting the fact that RTs were faster on trials where cue colors and target colors matched relative to trials where they differed ($M = 583$ vs. 671 ms). Finally, and importantly, there was a significant main effect of Target Color ($F(1, 11) = 22.43$, $p = .001$, $\eta_p^2 = .67$), as target RTs were generally

faster for targets in the expected versus unexpected color (M = 595 vs. 659 ms).[1]

A matching ANOVA on error rates showed no significant main effect of Cue Validity and no interaction between Cue Validity and Cue Color (both $F < 1$). There was however a reliable Cue Color × Target Color interaction ($F(1, 11) = 8.07$, $p = .02$, $\eta_p^2 = .42$), as errors were less frequent on trials where cue and target colors were matched relative to trials where they differed ($M = 5\%$ vs. 8%). Errors were also less frequent on trials where the target had the expected as compared to unexpected color (M = 5% vs. 8%; main effect of Target Color: $F(1, 11) = 8.76$, $p = .01$, $\eta_p^2 = .44$).

Discussion of Experiment 1

In the 50–50 task, reliable spatial cueing effects indicative of task-set contingent attentional capture were found, confirming previous observations (Grubert & Eimer, 2016; Irons et al., 2012) and indicating that two color-specific search templates can be maintained concurrently. The critical new insight provided by the 80–20 task was that these spatial cueing effects were insensitive to participants' expectations about target color probabilities. Significant cueing effects were triggered both by cues that matched the more likely target color as well as by cues that matched the less likely color, and, critically, the magnitude of these effects did not differ between these two types of cues. This observation suggests that the activation states of attentional templates exclusively reflect the relevance of particular features, and cannot be adjusted in line with the likelihood that a specific feature will be relevant for an upcoming target selection process.

This absence of any target-color expectation effects on the ability of color cues to attract attention stands in marked contrast to the clear impact of target color probability on RTs in response to search targets, which were more than 60 ms faster when search displays included the expected-color target. This observation is in line with classic reports of target probability effects (e.g., Hyman, 1953), and demonstrates that the apparent insensitivity of preparatory attentional templates to color expectations was not due to participants simply ignoring the relative probabilities of the two target colors in the 80–20 task. The striking dissociation between the absence of any expectation-induced effects on preparatory template activation processes and the presence of large expectation effects on RTs to search targets revealed in Experiment 1 could suggest that these two types of effects are associated with different visual processing stages. The attentional capture by template-matching cues is likely to operate at relatively early visual-perceptual stages, whereas the effects of color probability on target RTs may be primarily generated at later response-related stages that follow the initial attentional selection of search targets. In this context, the results of Experiment 1 could be interpreted as further evidence for the hypothesis that relevance modulates perceptual processing, whereas expectation-induced effects primarily affect later post-perceptual stages (e.g., Kinchla, 1992).

Experiment 2 was conducted to put this interpretation to a critical test. Participants completed the same 80–20 two-color search task as in Experiment 1, and EEG was recorded during task performance, in order to measure N2pc components as electrophysiological markers of the allocation of attention to objects with template-matching colors. N2pcs were computed separately for

color cues that matched the more versus less likely target color, and for search displays that included either an expected-color or an unexpected-color target. If template activation states are unaffected by expectation, behavioral spatial cueing effects should not differ in size for cues in the expected versus unexpected target color, as was observed in the 80–20 task of Experiment 1. Critically, these two cues should also trigger identical N2pc components, thereby demonstrating that their ability to attract attention was not modulated by expectations about upcoming target colors. Responses to search displays in Experiment 2 should again be faster when these displays contain the more likely target-color object. If this expectation-induced behavioral effect was generated at late response-related stages that follow the color-guided attentional selection of target objects, it should not be reflected by a corresponding N2pc difference. Thus, N2pc components triggered by expected-color versus unexpected-color target objects should not differ in terms of their amplitudes or onset latencies, and thus mirror the predicted absence of differential N2pc effects for the two color cues.

Another finding of Experiment 1 was that search performance was generally superior on trials where cue and target colors matched relative to trials where these colors were different. This pattern was observed in the 50–50 and in the 80–20 tasks, and confirms analogous observations from previous studies of two-color search that employed spatial cueing procedures (Grubert & Eimer, 2016; Irons et al., 2012; see also Moore & Weissman, 2010, 2011). Different mechanisms have been suggested for such cue–target color repetition benefits. According to Moore and Weissman (2010, 2014), the detection of a distractor object with a template-matching feature results in a transient boost in the activation of the corresponding search template. This will facilitate the subsequent allocation of attention to target objects that match this template relative to targets matching a different template. Alternatively, cue-target color repetition benefits may be primarily generated at later stages that follow attentional target selection, such as working memory access and response selection (as suggested tentatively by Irons et al., 2012). To test these alternative interpretations, we also measured target N2pcs in Experiment 2 separately for trials where a target either matched or did not match the color of a preceding cue. If the transient template activation account proposed by Moore and Weissman (2010, 2014) was correct, N2pc components to target objects should emerge earlier when these targets were preceded by a color-matching cue.

Using the N2pc as an independent online marker of attentional capture by cues in the expected versus unexpected target color is important to provide additional evidence for the hypothesis that capture is unaffected by color-specific expectations. In Experiment

---

[1] There was also a reliable main effect of Cue Color for RTs, reflecting generally faster RTs on trials where the cue matched the unexpected target color ($M = 614$ vs. 640 ms; $F(1,11) = 24.18$, $p < .001$, $\eta_p^2 = .69$). This was due to the fact that cue-target mismatch costs were much larger on trials where a cue that matched the expected target color was followed by a target in the other unexpected color than on trials where an expected-color target was preceded by an unexpected-color cue (see Table 1). Because the former trials were infrequent, they contributed disproportionately to the factorial ANOVA. When directly comparing all trials with cues that matched the expected versus unexpected target color, an effect in the opposite direction was evident, with faster RTs for cues that matched the more likely target color ($M = 604$ vs. 628 ms; $t(11) = 3.26$, $p = .008$).

1, this conclusion was based on the observation that both color cues triggered equivalent spatial cueing effects on target RTs in the 80–20 task. However, the fact that these RTs differed between trials with expected-color and unexpected-color targets, and also between trials with matching versus mismatching cue and target colors, makes it difficult to ascertain that these spatial cueing effects were in fact identical in size. Because the N2pc is a direct electrophysiological response to the cue that is unaffected by any subsequent target-related processing, it provides a more direct measure of any effects of expectations about target colors on cue-induced attentional capture.

Experiment 2

Method

Participants. Twelve participants took part in Experiment 2 (*M* age = 31 years, *SD* = 6; 5 male; 2 left-handed). All reported normal or corrected-to-normal vision and were naïve to the experimental hypotheses. Reaction time data for targets at cued versus uncued locations (averaged across both cue colors) from the 80–20 task of Experiment 1 were used to assess achieved power (M = 649 vs. 605 ms, resulting in dz = 1.67). Assuming an alpha level of .05 and power of .80, this analysis provided a recommended minimum sample size of *N* = 6. As Experiment 2 also measured electrophysiological responses, we additionally utilized previous data from our lab from experiments that measured N2pc components to color cues that preceded search displays in task-set contingent attentional capture experiments (Eimer & Kiss, 2008; Grubert & Eimer, 2016). The effect size obtained in these experiments suggested that minimum sample sizes of approximately 6–8 participants were required to measure reliable N2pc components to target-matching color cues. To guarantee sufficient power, and to provide comparisons with Experiment 1, the same sample size of 12 participants was tested in Experiment 2.

Stimuli and procedure. These matched the 80–20 task of Experiment 1, with the following exceptions. The interval between cue and target arrays was now increased from 50 ms to 150 ms, in order to permit the recording of cue-elicited N2pc components prior to the onset of ERP activity triggered by target arrays. Participants' responses were now recorded using a response box with a four-button layout arranged in cardinal directions, where only the top and bottom buttons were used (Black Box Toolkit; The Black Box Toolkit, Ltd., 2016). Participants responded by pressing the bottom button for a horizontally oriented target, and the top button for a vertically oriented target. In half of the blocks, they responded to horizontal targets using their left hand and vertical targets using their right hand, with this assignment swapped for the other half of the blocks (order counterbalanced across participants). The experiment consisted of 24 blocks, each containing 40 trials.

EEG recording and data analysis. EEG was DC-recorded at 27 scalp electrodes, mounted on an elastic cap at 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 applied. A left-earlobe electrode was used as an online reference, with the average of both earlobes used for offline re-referencing. No other filters were applied. Trials with eyeblinks (exceeding ±60 μV at Fpz), hori-

zontal eye movements (exceeding ±30 μV in the HEOG channels), and muscle movement artifacts (exceeding ±80 μV at all other channels) were removed, in addition to trials with incorrect responses. The remaining trials were segmented into epochs and averaged. ERPs to cue displays were computed within a period between 0 ms and 500 ms after cue display onset, relative to a 100-ms prestimulus baseline. ERPs to search displays were computed between 200 ms before to 500 ms after display onset, relative to a 100 ms baseline prior to the onset of the cue display on that trial. For cues, ERPs were computed separately for cue displays containing a color cue on the left versus right side that matched either the expected or unexpected target color. For search displays, ERPs were computed separately for displays containing an expected-color versus unexpected-color target on the left versus right side. For both cue and search displays, N2pc components were quantified based on ERP mean amplitudes obtained at lateral posterior electrode sites PO7/PO8 between 200 and 300 ms after the onset of the corresponding display. N2pc onset latency differences between cues/targets matching the expected versus unexpected target color were assessed on the basis of N2pc difference waveforms (computed by subtracting ipsilateral from contralateral ERPs at PO7 and PO8) with a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998). Twelve grand-average difference waves were computed separately for the two cue/target colors, with each difference wave excluding one different participant from the original sample. For cue displays, N2pc onset was defined with a fixed onset criterion of −0.5 μV. For target displays, where N2pc components were substantially larger (see below), an onset criterion of −1 μV was employed. For both displays, N2pc onset latencies for displays containing an object in the expected or unexpected target color were compared with paired *t* tests. All *t*-values were corrected according to the formulas described by Miller et al. (1998), indicated by t_c. Finally, additional analysis compared N2pc onset latencies elicited by search targets on trials where cue and target colors were either identical or differed, separately for targets in the expected and unexpected color, using *F* tests that were corrected according to the formula described by Ulrich and Miller (2001), indicated by F_c.

Results

Performance. Mean RTs and error rates are shown in Table 1 (bottom panel), separately for trials where the cue color matched the expected (80%) or the unexpected (20%) target color. RT data from trials with correct responses were entered into a 2 × 2 × 2 ANOVA with the factors Cue Color (matching the expected vs. unexpected target color), Target Color (expected vs. unexpected), and Cue Validity (target at cued vs. uncued location). A main effect of Cue Validity ($F(1, 11) = 5.70$, $p = .04$, $\eta_p^2 = .34$) reflected the presence of reliable spatial cueing effects, with faster RTs for targets at cued versus uncued locations (*M* = 606 vs. 618 ms). Critically, and confirming the results of Experiment 1, there was no interaction between Cue Validity and Cue Color ($F < 1$), as spatial cueing effects were similar in size for cues in the expected and unexpected target color (*M* = 13 vs. 9 ms). As in Experiment 1, there was a significant Cue Color × Target Color interaction ($F(1, 11) = 16.82$, $p = .002$, $\eta_p^2 = .61$), due to the fact that RTs were faster on trials where the cue color matched the subsequent target color relative to trials where these two colors

were different ($M = 597$ vs. 627 ms). Finally, there was again a main effect of Target Color ($F(1, 11) = 11.64$, $p = .006$, $\eta_p^2 = .51$), as RTs were faster on trials where the target appeared in the expected color relative to trials with the other unexpected color target ($M = 638$ vs. 586 ms). There was no main effect of Cue Color, $F(1, 11) = 1.15$, $p = .31$, and no other interactions between factors (all $Fs < 1$).[2] A matching analysis of error rate data showed only a significant main effect of Cue Validity ($F(1, 11) = 5.51$, $p = .04$, $\eta_p^2 = .33$), with errors more frequent on trials where targets appeared at uncued locations ($M = 7$ vs. 5%). There were no main effects of Target Color, $F(1, 11) = 1.41$, $p = .26$, or Cue Color ($F < 1$), and no interactions (all $Fs < 1$).

N2pc results.

Cue displays. Figure 2 shows ERPs elicited by cue displays at electrodes PO7/PO8 contralateral and ipsilateral to the side of the color singleton cue in the 350-ms interval following cue display onset. ERPs are shown separately for displays containing the expected or unexpected target color, together with the corresponding contralateral-ipsilateral difference waveforms. Clear N2pcs were triggered by both types of cues, and there was no apparent difference in the amplitudes and onset latencies of these components. This was confirmed by statistical analyses. N2pc mean amplitudes obtained 200–300 ms poststimulus onset were entered into a 2×2 ANOVA with the factors Cue Color (matching the expected vs. unexpected target color) and Laterality (Ipsilateral, Contralateral). A main effect of Laterality ($F(1, 11) = 23.62$, $p = .001$, $\eta_p^2 = .68$) confirmed the reliable presence of N2pc components in response to cue displays. Importantly, there was no interaction between Laterality and Cue Color ($F < 1$), demonstrating that cues in the expected and unexpected target color elicited N2pc components of equivalent size. Planned follow-up t tests comparing contralateral and ipsilateral ERPs confirmed the presence of significant N2pc components for cues matching the expected target color (M diff $= .97$ μV; $t(11) = 4.23$, $p = .001$), as well as for cues matching the unexpected target color (M diff $= -1.12$ μV; $t(11) = 4.95$, $p < .001$). To investigate possible onset latency differences between these two N2pc components, a jackknife-based procedure with an absolute onset criterion of -0.5 μV was employed (see Method). There was no difference in the onsets of N2pcs to cues matching the expected and unexpected target color ($M = 192$ vs. 188 ms; $t_c < 1$).

Search displays. Figure 3 shows ERPs elicited by search displays at PO7/PO8 contralateral and ipsilateral to the side of the target, in the interval between cue display onset and 500 ms after target display onset, relative to a 100-ms precue baseline. ERPs are shown separately for search displays containing a target object in the expected or unexpected color (averaged across both colors and all possible locations of the preceding color cues). The y-axes mark the onset of the search display, and the ERP components visible prior to search display onset reflect visual responses to the preceding cue display. The corresponding contralateral–ipsilateral N2pc difference waveforms are shown at the bottom. As expected, both types of targets triggered clear N2pc components, but these N2pcs were larger and emerged earlier for expected-color as compared to unexpected-color targets. This was confirmed statistically. A 2×2 ANOVA conducted for ERP mean amplitudes elicited in the 200–300-ms interval after search display onset with the factors Target Color and Laterality obtained a main effect of Laterality ($F(1, 11) = 23.84$, $p < .001$, $\eta_p^2 = .68$), demonstrating

the presence of reliable target N2pc components. Importantly, there was a significant Target Color $\times$ Laterality interaction ($F(1, 11) = 8.93$, $p = .01$, $\eta_p^2 = .45$), confirming the observation that N2pcs were larger for targets in the expected color. Analyses conducted separately for both color targets showed that N2pcs were reliably present both for the expected color target (M diff $= -1.83$ μV; $t(11) = 5.48$, $p < .001$) as well as for the unexpected color target (M diff $= -.89$ μV; $t(11) = 2.93$, $p = .01$). A jackknife-based N2pc onset latency comparison based on a fixed criterion of -1 μV showed that N2pc components emerged earlier when search displays contained the expected as compared to the unexpected color target ($M = 208$ vs. 240 ms; $t_c(11) = 2.19$, $p = .05$).[3]

Because the behavioral data from both experiments consistently showed target RT benefits on trials where cue and target colors were identical, we also assessed N2pc components elicited by targets whose color matched the color of the preceding cue and by targets in a color that differed from the cue color on the same trial. N2pc difference waveforms obtained for these two types of trials by subtracting ipsilateral from contralateral ERPs are shown in Figure 4 (solid vs. dashed lines), separately for targets in the expected and unexpected color (black vs. gray lines). Target N2pcs emerged earlier on cue-target color match trials relative to mismatch trials. The N2pc onset difference between expected-color versus unexpected-color targets is also evident, but the cue-target color match effects on N2pc latencies appear to be present for both types of targets. This was confirmed by an ANOVA of N2pc onset latencies (again based on a fixed criterion of -1 μV) with the factors Target Color and Cue–Target Match (same color vs. different color). A significant main effect of Target Color ($F_c(1,11) = 15.90$, $p = .002$) confirmed the earlier onset of N2pcs to targets in the expected color ($M = 206$ vs. 244 ms). A significant main effect of Cue-Target Match ($F_c(1,11) = 10.07$, $p = .009$) demonstrated that target N2pc components emerged earlier on trials where cue and target colors matched relative to color-mismatch trials ($M = 214$ vs. 237 ms). There was no interaction between these factors ($F_c < 1$), indicating that the effects of Target Color and Cue-Target Match on N2pc onset latencies were independent. A corresponding analysis of target N2pc mean amplitudes obtained in the 200–300-ms interval after search display onset with Laterality as an additional factor found only a marginal interaction between Cue–Target Match and Laterality ($F(1, 11) = 3.44$, $p = .09$, $\eta_p^2 = .24$), reflecting a tendency toward larger target N2pc amplitudes on trials where cue and target colors matched (M diff $= -1.63$ vs. -1.16 μV).

---

[2] As Experiment 2 contained twice as many trials as the 80–20 task of Experiment 1, we used the RT data from this experiment to investigate whether intertrial color priming modulated attentional capture by either target-color cue. An analysis that included the additional factor Previous Target Color (expected, unexpected) found no evidence for such intertrial priming effects. There was no interaction between Cue Validity and Previous Target Color ($F(1,11) = 1.15$, $p = .31$) and no three-way interaction (Cue Validity $\times$ Cue Color $\times$ Previous Target Color; $F < 1$).

[3] The onset criterion employed for target N2pcs was higher than the criterion for cue N2pcs because the N2pc triggered by search targets was about twice as large as the N2pc elicited by color cues. When the lower N2pc onset criterion that was used for the analysis of cue N2pcs (-0.5 μV) was employed instead, this onset latency difference remained present ($M = 194$ vs. 224 ms; $t_c(11) = 3.83$, $p = .003$).

Cue in Expected Target Color

Cue in Unexpected Target Color

N2pc Difference Waves
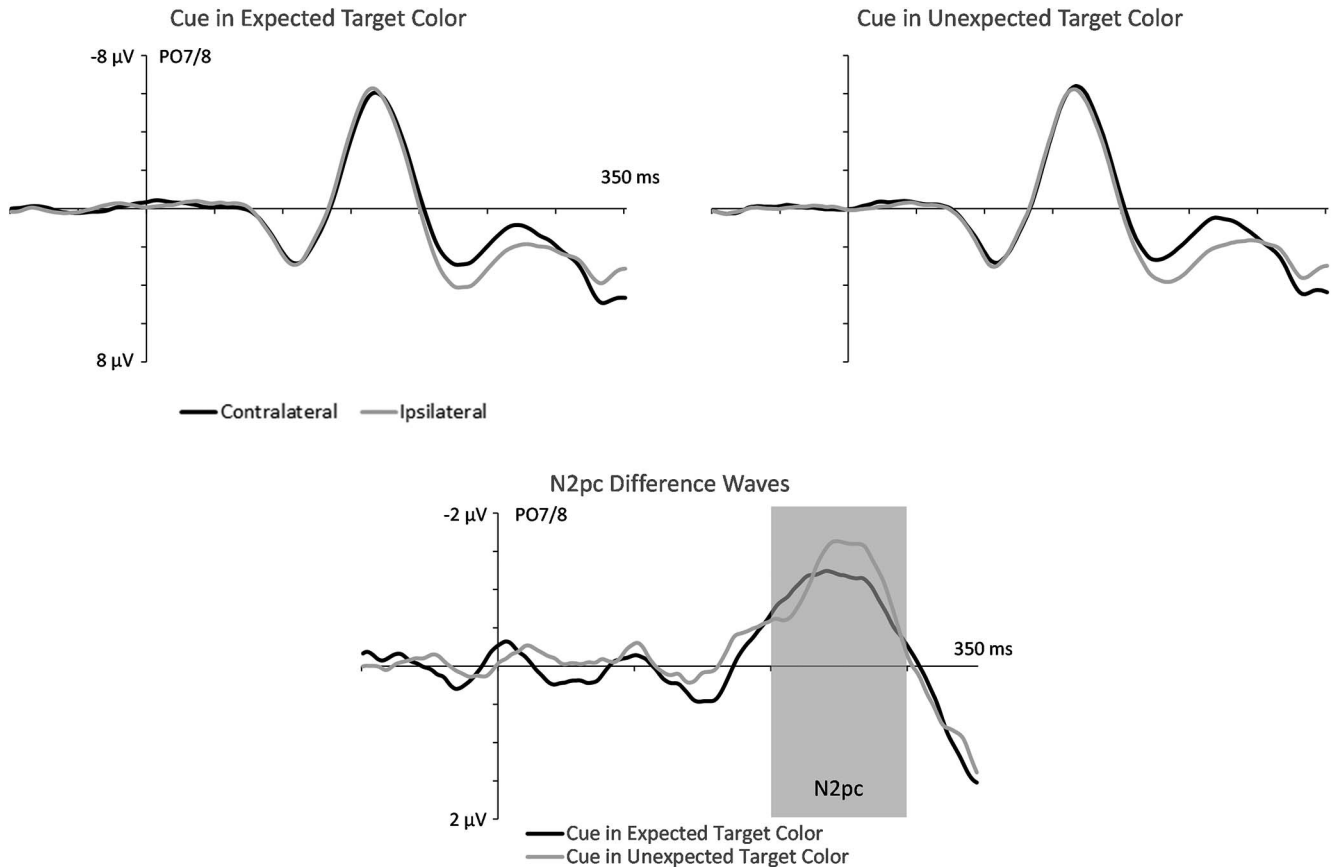
Figure 2. Top panels: Grand average ERPs obtained in Experiment 2 in the 350-ms interval following cue display onset at posterior electrode sites PO7/PO8 contralateral and ipsilateral to the side of the color singleton cue. ERPs are shown relative to a 100 ms prestimulus baseline, separately for cue displays containing an item in the expected or unexpected target color. Bottom panel: Difference waveforms computed by subtracting ipsilateral from contralateral ERPs, for cues in the expected or unexpected target color. The N2pc measurement window is highlighted.

Discussion of Experiment 2

Confirming the results of the first experiment, Experiment 2 found behavioral spatial cueing effects indicative of attentional capture that were again unaffected by whether cues matched the expected or unexpected target color. This suggests that task-set contingent attentional capture was exclusively determined by the relevance of these color cues, but not by expectations about the likely color of the upcoming target. Although behavioral spatial cueing effects were reliable in Experiment 2, they were considerably smaller than in Experiment 1. This difference is likely to be due to the fact that the interval between cue and search displays was 100 ms longer in Experiment 2 (150 ms vs. 50 ms). If the attentional capture by target-color cues is transient, spatial cueing effects should be maximal when search displays follow cues in rapid succession, and decrease in size as the cue–target interval gets longer.

Most importantly, Experiment 2 provided new electrophysiological support for the hypothesis that cue-induced attentional capture is insensitive to expectations about target colors. Both color cues triggered reliable N2pc components, demonstrating that

they attracted attention. Critically, the N2pcs triggered by cues in the expected and unexpected target color emerged at the same time and did not differ in size, demonstrating that expectations about the probability of target colors had no impact on the strength of attentional capture by color cues. These results show that attentional templates for either target color were activated equally strongly, in spite of the fact that one of these two templates was much more likely to be involved in an upcoming target selection process.

In marked contrast to the behavioral and electrophysiological correlates of task-set contingent attentional capture, which were entirely insensitive to target color expectations, clear expectation effects were observed for the processing of search targets. As in Experiment 1, target RTs were faster for expected as compared to unexpected color targets. This effect could in principle have been generated at late response-related stages that follow the attentional selection of search targets. However, the pattern of target N2pc components observed in Experiment 2 demonstrated that this was not the case. Targets in the expected color triggered earlier and larger N2pcs than unexpected-color targets (see Figure 3), indicat-
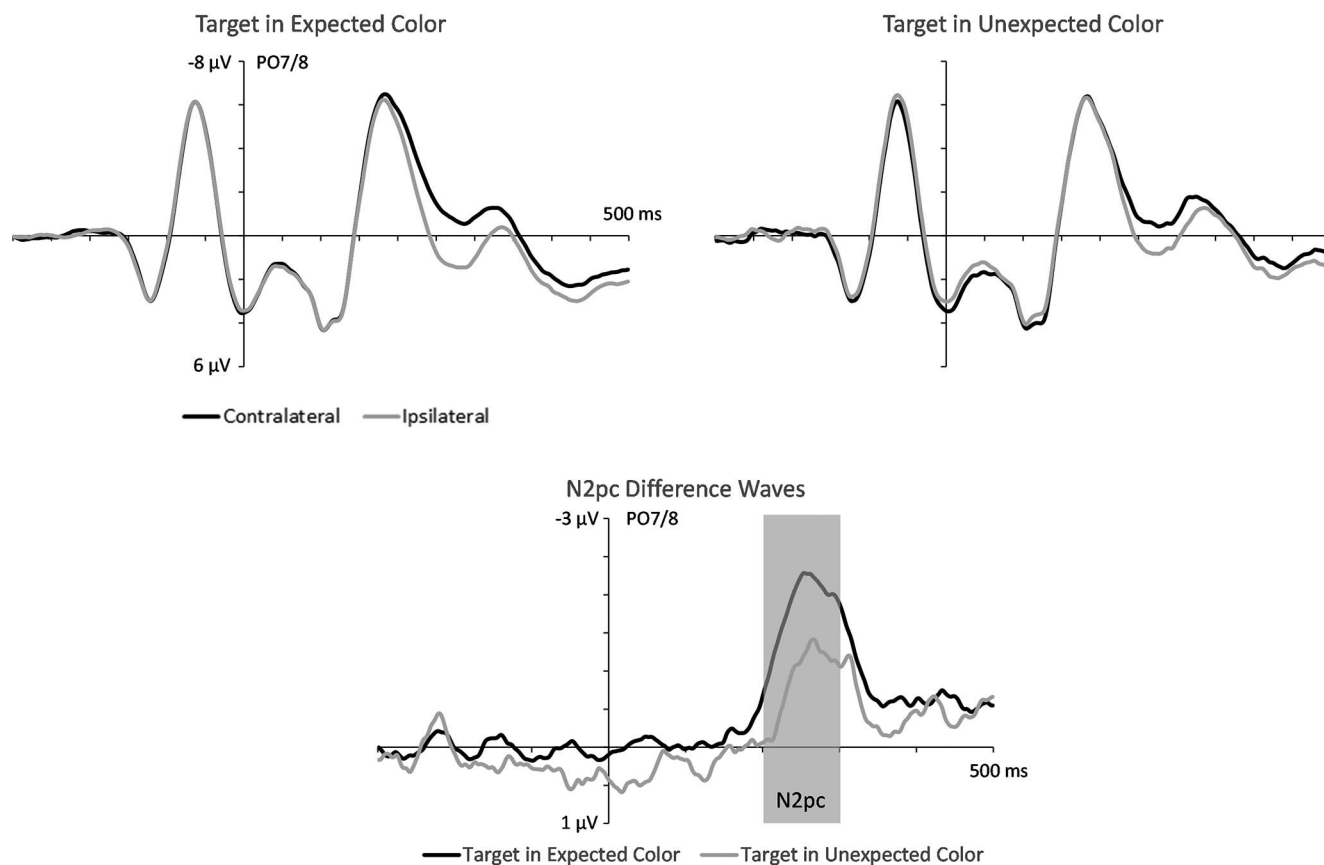
Figure 3. Top panels: Grand average ERPs obtained in Experiment 2 in the 500-ms interval following search display onset at posterior electrode sites PO7/PO8 contralateral and ipsilateral to a color target. The y-axes indicate search display onset, and ERPs are shown relative to a 100 ms baseline relative to cue display onset. The ERP components elicited prior to search display onset are visual responses to the preceding cue display. ERPs are shown separately for target objects in the expected or unexpected color. Bottom panel: Difference waveforms with the N2pc measurement window is highlighted.

ing that expectations affected the speed of attentional target selection processes within about 200 ms after search display onset. It is notable that the RT difference between search displays with expected versus unexpected color targets roughly matched the corresponding N2pc onset latency difference between these two types of targets. This suggests that the effects of color expectations on search performance can be mainly accounted for by differences in the speed with which attention is allocated to expected versus unexpected color targets, without major additional contributions from later post-perceptual processing stages.

Experiment 2 also confirmed the presence of RT benefits on trials where the colors of cues and targets were identical relative to trials where their colors differed. Notably, this behavioral effect was also reflected by corresponding N2pc onset latency differences. Target N2pcs emerged earlier on trials with matching cue and target colors (see Figure 4), suggesting that the cue-target color relationship primarily affected relatively early attentional allocation mechanisms. This finding supports the proposal of Moore and Weissman (2010, 2014) that the presentation of a task-irrelevant object that matches a current color-specific search template triggers a transient increase in the activation of this

template, which results in an expedited selection of color-defined targets that match this template relative to targets in a different color.

Overall, the results of Experiment 2 provide online electrophysiological evidence for a surprising dissociation in the effects of target color expectations on the attentional processing of target-matching color cues and color-defined search targets. While these expectations had no impact at all on the ability of color cues to attract attention, they strongly affected the allocation of attention to subsequent search targets, in spite of the fact that cue and search display onsets were separated by only 200 ms.

Experiments 3 and 4

While the results observed in Experiments 1 and 2 suggest a clear dissociation between the effects of color expectations on cue-induced attentional capture and on the subsequent attentional processing of search targets, alternative explanations remain viable. Experiments 3 and 4 were conducted to test these alternatives, with behavioral measures.

N2pc Difference Waves
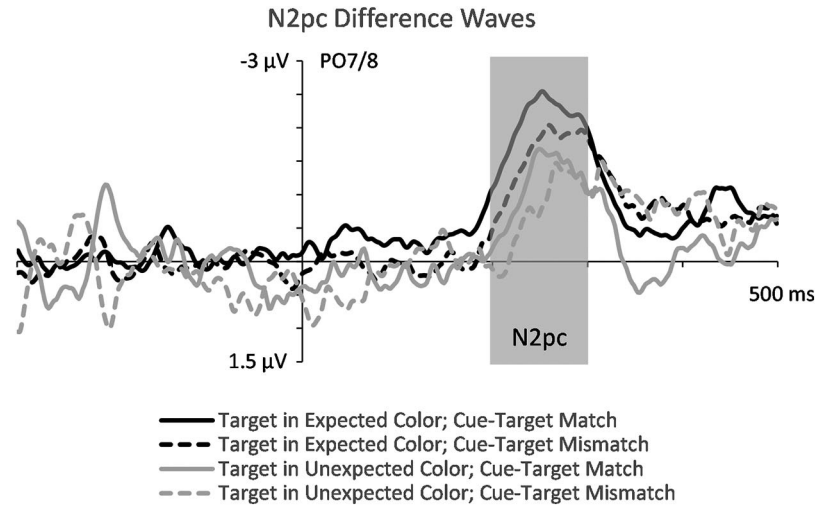
Figure 4. N2pc difference waveforms computed by subtracting ipsilateral from contralateral ERPs at PO7/8, for search displays in Experiment 2. The four difference waveforms show N2pcs for targets in the expected or unexpected color (black vs. gray lines), separately for trials where cue and target colors matched (solid lines) or did not match (dashed lines). ERPs are shown for the interval from cue onset to 500 ms after search display onset, relative to a 100-ms baseline prior to cue onset. The *y*-axis represents search display onset, and the N2pc measurement window is highlighted.

It is possible that the target-color cues employed in the first two experiments captured attention in a salience-driven bottom-up fashion that was unaffected by any top-down control settings related to expectation or relevance. Because these color cues were feature singletons, they may have attracted attention simply because they were the most salient items in the cue displays. A related possibility is that because search targets were always defined by their color, the task-relevance of the color dimension may have resulted in all color cues attracting attention equally, regardless of whether they matched the expected or unexpected target color. If either of these accounts was correct, spatial cueing effects and N2pc components triggered by these color cues would not reflect the activation of color-specific attentional templates. These interpretations are not supported by previous behavioral and electrophysiological investigations of task-set contingent attentional capture during feature-guided visual search tasks. These studies have consistently shown that color singleton cues only capture attention and elicit N2pc components when they match a current color task-set but not when their color is task-irrelevant (e.g., Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992; Grubert & Eimer, 2016, 2018; Irons et al., 2012). This makes it unlikely that the spatial cueing effects observed in Experiments 1 and 2 were the result of the bottom-up salience of cue stimuli, and/or the task-relevance of the color dimension. However, these two experiments differed from previous studies of contingent capture in several aspects. In most of these earlier studies, trials with nontarget-color cues were included, and participants typically searched for a single target color (but see Grubert & Eimer, 2016; Irons et al., 2012, for color-selective spatial cueing effects during two-color search). Given these differences, it is important to rule out conclusively that the spatial cueing effects observed in Experiments 1 and 2 reflect a type of attentional capture that is not sensitive to cue color. This was the goal of

Experiment 3, which employed the same 80–20 task as in Experiment 1. Critically, on one third of all trials, cue displays included a color singleton item that matched neither of the two target colors. If color cues captured attention because of their physical salience, or because the color dimension was task-relevant, these nontarget-color cues should produce the same spatial cueing effects as the two target-color cues in Experiment 3. Alternatively, if attentional capture was feature-specific, such cueing effects should only be found for target-color but not for nontarget-color cues.

Experiment 4 tested a different alternative interpretation of the results observed in the first two experiments. It is not inconceivable that participants may have maintained two separate sets of color expectations for cue and target displays, respectively, in spite of the fact that the cue displays were entirely task-irrelevant. Because cue displays were equally likely to contain either of the two target colors, any cue-specific color expectations would have resulted in both color cues attracting attention to the same degree. In Experiment 4, search displays were equally likely to contain either of the two color-defined target objects, as in the 50–50 task of Experiment 1. However, one of the two target colors now appeared in 80% of all cue displays, and the other in 20%. Because there were no differential expectations related to the likelihood of the two color targets, any differences in the spatial cueing effects elicited by the two color cues will exclusively reflect cue-specific expectations in Experiment 4. If such expectations were active, reliably larger cueing effects should be observed for trials where a cue in the more likely color was presented.

Method

Participants. Twelve participants took part in Experiment 3 (*M* age = 24 years, *SD* = 6, 4 male; 2 left-handed). Twelve participants took part in Experiment 4 (*M* age = 25 years, *SD* =

7; 4 male; 2 left-handed). All participants in both experiments reported normal or corrected-to-normal vision.

Stimuli and procedure. Experiment 3 was similar to the 80–20 task of Experiment 1 except that, on a third of trials, cue displays contained a nontarget-color cue. On the remaining two thirds of trials, cue colors were equally likely to match the expected or unexpected target color. To fully counterbalance the expected and unexpected target colors and the additional nontarget color used in some cue displays, these colors were selected from a constant set of three colors (red, blue, and green). Color assignments were rotated across participants. The nontarget color used in cue displays also appeared in all search displays as the color of one nontarget bar. Following practice, participants completed 18 experimental blocks of 40 trials.

Experiment 4 was similar to the 50–50 task of Experiment 1. Search displays included one of two equally likely color-defined targets. One of these two target colors now appeared in 80% of all cue displays, and the other in 20%. Following practice, participants completed 20 experimental blocks of 40 trials each.

Results

Experiment 3. Mean RTs and error rates are shown in Table 2 (top panel), separately for trials where the cue matched the expected target color, the unexpected target color, or a nontarget color. RT data on trials with correct responses were entered into a $3 \times 2 \times 2$ ANOVA with the factors Cue Color (matching the expected target color, unexpected target color, or the nontarget color), Target Color (expected vs. unexpected), and Cue Validity (target at cued vs. uncued location). There was no main effect of Cue Validity, $F(1, 11) = 1.08$, $p = .32$, but a significant Cue Color $\times$ Cue Validity interaction was present ($F(2, 22) = 13.29$, $p < .001$, $\eta_p^2 = .55$). Reliable spatial cueing effects were observed for cues that matched the expected target color (M diff $= 20$ ms; $t(11) = 2.77$, $p = .02$) or the unexpected target color (M diff $= 19$ ms; $t(11) = 2.55$, $p = .03$). These effects did not differ in size ($t < 1$). In contrast, and critically, nontarget-color cues did not trigger faster RTs for targets at cued versus uncued locations. In fact, there was a tendency for a reversed spatial cueing effect for nontarget-color cues that approached significance (M diff $= -19$ ms; $t(11) = 2.06$, $p = .06$). The cueing effects elicited by cues matching either the expected or unexpected target color both differed significantly from the effect observed for nontarget-color cues (ts > 3.60, ps $< .005$).

As in previous experiments, a significant Cue Color $\times$ Target Color interaction was present ($F(2, 22) = 69.57$, $p < .001$, $\eta_p^2 = .86$). On trials with target-color cues, RTs were faster when cue and target colors matched than when they did not match ($M = 587$ vs. 648 ms; $t(11) = 10.31$, $p < .001$). There was always a cue-target color mismatch on trials with nontarget-color cues. RTs on these trials ($M = 606$ ms) were reliably slower than RTs on cue-target color match trials, and faster than on trials where a target-color cue did not match the subsequent target color (ts > 4.27, ps $\leq .001$). Finally, and analogous to the 80–20 tasks of Experiments 1 and 2, a main effect of Target Color was present ($F(1, 11) = 21.54$, $p = .001$, $\eta_p^2 = .66$), as RTs were again faster for targets in the expected versus unexpected color ($M = 574$ vs. 654 ms).[4]

A matching analysis of error rates showed a significant main effect of Cue Validity ($F(1, 11) = 8.64$, $p = .01$, $\eta_p^2 = .44$), as response errors were more frequent on invalid trials ($M = 6\%$ vs. 4%). There was also a significant main effect of Target Color ($F(1, 11) = 4.97$, $p = .048$, $\eta_p^2 = .31$), with fewer errors in response to targets in the expected color ($M = 4\%$ vs. 6%). There was no significant main effect of Cue Color ($F < 1$), and no interactions (all Fs < 1.70, ps $> .20$).

Experiment 4. Mean RTs and error rates are shown in Table 2 (bottom panel), separately for trials where the cue appeared in the more likely or less frequent color (80% vs. 20%). RT data were entered into a $2 \times 2 \times 2$ ANOVA with factors Cue Color (frequent vs. infrequent), Target Color (matching the frequent vs. infrequent cue color), and Cue Validity (target at cued vs. uncued location). There was a main effect of Cue Validity ($F(1, 11) = 7.74$, $p = .02$, $\eta_p^2 = .41$), indicating reliably faster RTs for targets at cued versus uncued locations ($M = 628$ vs. 649 ms). Critically, there was no significant Cue Color $\times$ Cue Validity interaction ($F(1, 11) = 2.81$, $p = .12$, $\eta_p^2 = .20$). Reliable spatial cueing effects were triggered by both color cues, and these effects were even numerically larger for cues in the less likely color ($M = 661$ vs. 631 ms; $t(11) = 2.59$, $p = .03$) than for cues in the expected color ($M = 638$ vs. 624 ms; $t(11) = 2.29$, $p = .04$). There was no main effect of Target Color, $F(1, 11) = 1.41$, $p = .26$, indicating that target RTs were not affected by the frequency with which either target color appeared in the preceding cue displays. However, there was a Target Color $\times$ Cue Validity interaction effect ($F(1, 11) = 6.48$, $p = .03$, $\eta_p^2 = .37$), due to the fact that cue validity effects were larger when search displays contained the more versus less frequent cue color ($M = 31$ ms vs. 11 ms). As in all previous experiments, a Cue Color $\times$ Target Color interaction ($F(1, 11) = 36.37$, $p < .001$, $\eta_p^2 = .77$) reflected the fact that RTs were faster on trials where cue and target colors matched relative to trials where they were different ($M = 595$ vs. 682 ms).

A similar pattern was observed for error rates. Errors were more frequent for targets at uncued versus cued locations (6% vs. 5%; main effect of Cue Validity ($F(1, 11) = 9.19$, $p = .01$, $\eta_p^2 = .46$), but there was no interaction between Cue Color and Cue Validity ($F < 1$). A significant Cue Color $\times$ Target Color interaction ($F(1, 11) = 5.76$, $p = .04$, $\eta_p^2 = .34$) reflected the fact that errors were less frequent on trials where cue and target colors matched relative to trials where they differed ($M = 5\%$ vs. 7%).

Discussion of Experiments 3 and 4

These two experiments ruled out several alternative interpretations of the pattern of results observed in Experiments 1 and 2. In Experiment 3, spatial cueing effects indicative of task-set contingent attentional capture were measured for cues that matched the expected target color, the unexpected target color,

---

[4] As in the 80–20 task of Experiment 1, a significant main effect of Cue Color was present ($F(2,22) = 6.42$, $p = .006$, $\eta_p^2 = .37$), due to the fact that RTs were slower on trials where the cue matched the expected target color ($M = 623$ ms) relative to trials with cues that matched either the unexpected target color ($M = 612$ ms; $t(11) = 2.29$, $p = .04$) or the nontarget color ($M = 606$ ms; $t(11) = 3.56$, $p = .004$). As can be seen in Table 2, this resulted from the fact that RTs were most strongly delayed on trials where a cue in the expected target color was followed by a target in the other unexpected color.

Table 2

Mean Reaction Time in Milliseconds (Upper Row) and Error Rate Percentages (Lower Row) in Experiments 3 and 4

	Experiment 3					
	Expected target color cue		Unexpected target color cue		Nontarget-Color Cue	
Target color	Invalid	Valid	Invalid	Valid	Invalid	Valid
Expected target color (80%)	566 (49)	536 (53)	606 (57)	597 (59)	560 (52)	575 (65)
	6 (4)	3 (2)	6 (4)	4 (4)	4 (3)	4 (6)
Unexpected target color (20%)	699 (100)	690 (92)	637 (91)	608 (104)	633 (96)	656 (120)
	9 (6)	5 (10)	5 (3)	3 (6)	6 (8)	5 (10)
	Experiment 4					
	Frequent cue color (80%)		Infrequent cue color (20%)			
	Invalid	Valid	Invalid	Valid		
Target in frequent cue color	608 (98)	584 (89)	716 (94)	678 (78)		
	6 (6)	4 (5)	7 (7)	5 (8)		
Target in infrequent cue color	668 (89)	665 (102)	605 (105)	584 (101)		
	8 (6)	6 (5)	5 (4)	3 (5)		

Note. Standard deviations are presented in parentheses.

or a task-irrelevant nontarget color. Reliable spatial cueing effects of equivalent size were observed for both types of target-color cues, confirming again that these cueing effects were not affected by expectations about target colors. Critically, no such RT benefits for targets at cued versus uncued locations were found for trials with nontarget-color cues. In fact, there was a tendency for RTs to be slower on trials with valid nontarget-color cues. Such inverse spatial cueing effects for cues in a task-irrelevant color have been observed in previous studies of task-set contingent attentional capture (e.g., Carmel & Lamy, 2014; Eimer, Kiss, Press, & Sauter, 2009; Lamy, Leber, & Egeth, 2004), and have been attributed to rapid inhibitory processes or related mechanisms (see Carmel & Lamy, 2014, for more details). The absence of positive spatial cueing effects for nontarget-color cues in Experiment 3 rules out the possibility that the effects found for target-color cues were driven by the physical salience of color singleton cues, or by the fact that the color dimension was task-relevant. This result demonstrates instead that the cues captured attention in a color-specific task-set contingent fashion.

Experiment 4 tested whether spatial cueing effects might reflect color expectations that were specific to cue displays, and thus unrelated to expectations about color-defined target objects in search displays. Both color targets were now equiprobable, but cue displays were much more likely to contain a color singleton that matched one of the two target colors. This manipulation did not result in increased spatial cueing effects for more probable color cue. In fact, there was a nonsignificant tendency in the opposite direction, with cueing effects being numerically larger for the less likely color cue. This observation demonstrates that the spatial cueing effects observed in Experiments 1 to 3 were not mediated by any expectations associated with the probability that a specific color would be present in a cue display, but were instead exclusively driven by the task-relevance of these colors.

General Discussion

The goal of the current study was to investigate whether the activation of preparatory attentional templates for target-defining features during visual search can be modulated in line with expectations about the likelihood of particular search targets. Participants searched for one of two possible color-defined target objects, and search displays were preceded by uninformative color cues that matched one of the two target colors. Critically, one of the two color targets was very likely to appear in a search display while the other target was presented only infrequently (80% vs. 20%). The question was whether this would affect the ability of matching color cues to capture attention, as reflected by task-set contingent spatial cueing effects. In both experiments, RTs were reliably faster for targets at cued as compared to uncued locations, indicating that target-matching color cues did indeed attract attention. However, and critically, no evidence for an effect of color expectation on attentional capture was found in either experiment, as spatial cueing effects did not differ in size for cues that matched the expected versus unexpected target color. This was confirmed in Experiment 2 by measuring N2pc components in response to color cues as ERP markers of attentional capture by these cues. N2pcs emerged at the same time and were equal in size for both types of cues, demonstrating that both attracted attention equally. These results strongly suggest that the activation states of multiple feature-specific attentional templates exclusively reflect the relevance of particular target features, and are insensitive to expectations about the likelihood that a specific target feature will be encountered during the next selection episode. It appears as if such templates are either "on" (for relevant features) or "off," and that their activation cannot be further adjusted in line with expectations about the relative probability of different targets.

While these expectations did not have any effect on the attentional processing of color cues, they strongly affected the subsequent processing of color targets. In Experiments 1-3, RTs were

faster for expected-color targets, in line with findings from classic experimental work (Fitts et al., 1963; Hyman, 1953). Expectation-induced effects on performance in attentional tasks have often been attributed to post-perceptual mechanisms that follow attentional selection (Kinchla, 1992). If relevance affects attentional selectivity at early perceptual stages of visual processing, and expectation only acts at subsequent postselection stages, this could explain why expectations had no impact on the ability of color cues to attract attention. However, the pattern of target N2pcs observed in Experiment 2 did not support such a separate-stage account for relevance and expectation effects. Targets in the expected color elicited earlier and larger N2pcs than unexpected-color targets, demonstrating that color expectations modulated the allocation of attention to search targets. Moreover, the delay of N2pcs for targets in the unexpected color matched the corresponding delay of target RTs, suggesting that the effects of expectation on the processing of search displays were exclusively generated during the attentional selection of target objects.

These results lead to an intriguing conclusion: Expectations about the likelihood of target colors have no impact on attentional capture by target-matching color cues, but systematically affect the speed of selecting color-defined targets in search displays that are presented only 100 ms (Experiment 1) or 200 ms (Experiment 2) after the cue displays. The allocation of attention to target-color cues is assumed to reflect the activation of preparatory attentional templates, and the same templates are believed to guide the allocation of attention to targets in visual search displays. In this context, the apparent dissociation in the effects of expectation on the attentional processing of cues and search targets is extremely puzzling. Experiment 3 demonstrated that this puzzle cannot be resolved by assuming that the attentional capture effects triggered by color cues in the 80–20 tasks of Experiments 1 and 2 were not color-selective, because they reflected either bottom-up attentional capture or the task-relevance of the color dimension. If this was correct, nontarget-color cues should have elicited equivalent spatial cueing effects, which was clearly not the case. Neither can the absence of expectation-related modulations of attentional capture in Experiments 1 and 2 be explained by the fact that both cue colors were equiprobable. Experiment 4 found spatial cueing effects of equivalent size for both target-color cues when one of them was much more likely to appear than the other. This shows that attentional capture effects were driven exclusively by the task-relevance of cue colors, and were not modulated by any separate task-unrelated expectations about probability of particular color cues.

Another possibility is that, in contrast to feature relevance, expectations about the probability of specific target features are tightly linked to predictions about the expected arrival of a search display, and therefore affect attentional selectivity in a temporally precise fashion. If such expectations refer to the likelihood that a particular target color is presented at a specific point in time, they would only affect the attentional processing of objects that appear at the predicted time (i.e., search targets) but not the processing of objects that are presented earlier (i.e., color cues). There is considerable evidence that attentional effects on visual processing can be affected by temporal expectations. In a recent study from our lab (Grubert & Eimer, 2018), the time course of target template activation processes during the preparation for search was tracked by measuring N2pc components to target-matching "probe" stim-

uli that appeared at different points in time during the interval between two successive search displays. During the early phase of this interval, these probes failed to attract attention, as indicated by the absence of N2pcs. Probe N2pcs emerged about 800 ms prior to the presentation of the next search display, and were maximal immediately prior to the expected arrival of this display. These results show that preparatory template activation states can be sensitive to predictions about the timing of target objects. Along similar lines, a recent behavioral study (Denison, Heeger, & Carrasco, 2017) found that attention-related enhancements of contrast sensitivity could be restricted to particular task-relevant time intervals. Because the onset of search displays was fully predictable in the present study, it is possible that an association between color-specific and temporal expectations was responsible for the fact that expectation-induced effects on attentional selectivity were only observed for search displays but not for cue displays. However, given these two types of displays were separated by only 100 or 200 ms, it may appear implausible that color-based expectations can be tuned in such a temporally precise way.

A different but related possibility is that expectations about target colors were associated not or not only with temporal expectations, but also with expectations about other properties of the target objects. In the present study, target objects were always rectangular bars, and participants' expectations may have been related not to colors as such, but to the probability that a particular target object (e.g., a red vs. green bar) would be present in the search displays. Because cue displays did not contain any bar-shaped items, such object-based expectations would not have applied to the color cues. Recent work examining the effects of expectations about individual features versus whole objects on the selective processing of visual input found initial evidence for such object-based effects. Jiang, Summerfield, and Egner (2016) manipulated expectations regarding the color or motion direction of moving color objects independently, and measured expectation-induced modulations of fMRI activity patterns. Results were consistent with a model that postulated a spread of feature-specific expectations to other features of the same object, thus altering expectations at an object-based level. Jiang et al. (2016) concluded that objects rather than individual features may be the primary unit of selection for visual prediction. Such an object-based locus of expectation-induced attentional effects could account for the presence of such effects on the processing of target objects and the absence of any expectation-sensitive modulations for the processing of color cues in the present study. It is also possible that such object-based expectations also include temporal predictions (as discussed above), and thus refer to particular colored target bars at specific points in time. The involvement of such temporal expectations could be investigated in future studies by manipulating the predictability of search display onsets, and testing whether this factor modulates the effects of color-specific expectations on the attentional processing of search targets. More generally, the hypothesis that task relevance applies to individual features whereas expectation acts in an object-based fashion suggests a fundamental dissociation in the way in which these two core aspects of goal-directed visual processing operate.

A consistent observation across all tasks used in the present study was that the relationship between cue and target colors affected search performance, with faster RTs on trials where the target color matched the preceding cue color relative to trials

where these colors were different. The same phenomenon has been observed in previous studies of two-color search (Grubert & Eimer, 2016; Irons et al., 2012). In Experiment 2, target N2pc components emerged reliably earlier on trials with identical cue and target colors relative to trials with a color mismatch, indicating that target objects were selected more rapidly when they were preceded by a cue in the same color. This conclusion is in line with previous suggestions by Moore and Weissman (2010, 2014) that task-irrelevant colored items can prioritize a corresponding color-specific search template, thus resulting in performance benefits when a subsequent target object matches this template. The N2pc results from Experiment 2 demonstrate for the first time that such benefits are generated at relatively early stages of attentional target selection, within about 200 ms after stimulus onset. If such color-specific facilitation effects persist across successive search episodes, this may also account for the existence of switch costs during multiple-color search, which have played a prominent role in current debates about the possibility of parallel attentional templates (e.g., Beck et al., 2012; Ort, Fahrenfort, & Olivers, 2018).

The existence of systematic cue-target color mismatch costs for performance and target N2pc onset latencies demonstrates that cue colors were detected and discriminated. This is important, because it rules out another possible explanation for the absence of expectation-related modulations of spatial cueing effects in terms of a failure in processing the colors of the task-irrelevant cues. It is notable that in the 80–20 task of Experiment 1, RT costs were most pronounced on trials where a cue that matched the expected target color was followed by a target in the other unexpected color. Exactly the same pattern was also observed in Experiment 3. These results suggest that presenting color cues, and the transient increase in the activity of color-specific search templates triggered by such cues, can modulate existing object-based expectations about subsequent targets. If encountering a cue in the expected target color further enhances the expectation for a matching color target, performance costs should be maximal on trials where the other unexpected color target is presented, as was indeed the case in Experiment 1. No such differential effects were evident in Experiment 2, where the interval between cue and target displays was increased from 50 ms to 150 ms, suggesting that any such cue-induced modulations of expectations related to target objects may be short-lived.

In summary, the present study has provided new insights into the roles of relevance and expectation in the control of attentional target selection processes during visual search. Preparatory attentional templates for different task-relevant colors were found to be activated in parallel, and these template activation states were insensitive to expectations with respect to the likelihood that a particular target color would be present in the next search episode. In contrast, color-based expectations strongly influenced the speed with which attention was allocated to search target objects. Relevance and expectation thus have dissociable effects on attentional preparation and target selection processes, which suggests qualitative differences in the way that these two parameters are specified at the level of executive control processes. The relevance of visual signals for a current attentional selection task is likely to be represented in a feature-based fashion, while the cognitive code in which expectations are expressed might be primarily object-based.

References

Adamo, M., Pun, C., Pratt, J., & Ferber, S. (2008). Your divided attention, please! The maintenance of multiple attentional control sets over distinct regions in space. *Cognition, 107,* 295–303. http://dx.doi.org/10.1016/j.cognition.2007.07.003

Beck, V. M., Hollingworth, A., & Luck, S. J. (2012). Simultaneous control of attention by multiple working memory representations. *Psychological Science, 23,* 887–898. http://dx.doi.org/10.1177/0956797612439068

Berggren, N., & Eimer, M. (2018). Visual working memory load disrupts template-guided attentional selection during visual search. *Journal of Cognitive Neuroscience, 30,* 1902–1915. http://dx.doi.org/10.1162/jocn_a_01324

Carmel, T., & Lamy, D. (2014). The same-location cost is unrelated to attentional settings: An object-updating account. *Journal of Experimental Psychology: Human Perception and Performance, 40,* 1465–1478. http://dx.doi.org/10.1037/a0036383

Denison, R. N., Heeger, D. J., & Carrasco, M. (2017). Attention flexibly trades off across points in time. *Psychonomic Bulletin & Review, 24,* 1142–1151. http://dx.doi.org/10.3758/s13423-016-1216-1

Duncan, J., & Humphreys, G. (1992). Beyond the search surface: Visual search and attentional engagement. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 578–588. http://dx.doi.org/10.1037/0096-1523.18.2.578

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology, 99,* 225–234. http://dx.doi.org/10.1016/0013-4694(96)95711-9

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience, 20,* 1423–1433. http://dx.doi.org/10.1162/jocn.2008.20099

Eimer, M., Kiss, M., Press, C., & Sauter, D. (2009). The roles of feature-specific task set and bottom-up salience in attentional capture: An ERP study. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1316–1328. http://dx.doi.org/10.1037/a0015872

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39,* 175–191. http://dx.doi.org/10.3758/BF03193146

Feldman, H., & Friston, K. J. (2010). Attention, uncertainty, and free-energy. *Frontiers in Human Neuroscience, 4,* 215. http://dx.doi.org/10.3389/fnhum.2010.00215

Fitts, P. M., Peterson, J. R., & Wolpe, G. (1963). Cognitive aspects of information processing: II. Adjustments to stimulus redundancy. *Journal of Experimental Psychology, 65,* 423–432. http://dx.doi.org/10.1037/h0047993

Folk, C. L., & Remington, R. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 847–858. http://dx.doi.org/10.1037/0096-1523.24.3.847

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1030–1044. http://dx.doi.org/10.1037/0096-1523.18.4.1030

Grubert, A., & Eimer, M. (2016). All set, indeed! N2pc components reveal simultaneous attentional control settings for multiple target colors. *Journal of Experimental Psychology: Human Perception and Performance, 42,* 1215–1230. http://dx.doi.org/10.1037/xhp0000221

Grubert, A., & Eimer, M. (2018). The time course of target template activation processes during preparation for visual search. *The Journal of Neuroscience, 38,* 9527–9538. http://dx.doi.org/10.1523/JNEUROSCI.0409-18.2018

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology, 45,* 188–196. http://dx.doi.org/10.1037/h0056940

Irons, J. L., Folk, C. L., & Remington, R. W. (2012). All set! Evidence of simultaneous attentional control settings for multiple target colors. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 758–775. http://dx.doi.org/10.1037/a0026578

Jiang, J., Summerfield, C., & Egner, T. (2016). Visual prediction error spreads across object features in human visual cortex. *The Journal of Neuroscience, 36,* 12746–12763. http://dx.doi.org/10.1523/JNEUROSCI.1546-16.2016

Kinchla, R. A. (1992). Attention. *Annual Review of Psychology, 43,* 711–742. http://dx.doi.org/10.1146/annurev.ps.43.020192.003431

Laberge, D., & Tweedy, J. R. (1964). Presentation probability and choice time. *Journal of Experimental Psychology, 68,* 477–481. http://dx.doi.org/10.1037/h0048691

Lamy, D., Leber, A., & Egeth, H. E. (2004). Effects of task relevance and stimulus-driven salience in feature-search mode. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 1019–1031. http://dx.doi.org/10.1037/0096-1523.30.6.1019

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1000–1014. http://dx.doi.org/10.1037/0096-1523.20.5.1000

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390,* 279–281. http://dx.doi.org/10.1038/36846

Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology, 35,* 99–115. http://dx.doi.org/10.1111/1469-8986.3510099

Moore, K. S., & Weissman, D. H. (2010). Involuntary transfer of a top-down attentional set into the focus of attention: Evidence from a contingent attentional capture paradigm. *Attention, Perception, & Psychophysics, 72,* 1495–1509. http://dx.doi.org/10.3758/APP.72.6.1495

Moore, K. S., & Weissman, D. H. (2011). Set-specific capture can be reduced by preemptively occupying a limited-capacity focus of attention. *Visual Cognition, 19,* 417–444. http://dx.doi.org/10.1080/13506285.2011.558862

Moore, K. S., & Weissman, D. H. (2014). A bottleneck model of set-specific capture. *PLoS ONE, 9,* e88313. http://dx.doi.org/10.1371/journal.pone.0088313

Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences, 15,* 327–334. http://dx.doi.org/10.1016/j.tics.2011.05.004

Ort, E., Fahrenfort, J. J., & Olivers, C. N. L. (2018). Lack of free choice reveals the cost of multiple-target search within and across feature dimensions. *Attention, Perception, & Psychophysics, 80,* 1904–1917. http://dx.doi.org/10.3758/s13414-018-1579-7

Smith, E. E. (1968). Choice reaction time: An analysis of the major theoretical positions. *Psychological Bulletin, 69,* 77–110. http://dx.doi.org/10.1037/h0020189

Soto, D., Hodsoll, J., Rotshtein, P., & Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends in Cognitive Sciences, 12,* 342–348. http://dx.doi.org/10.1016/j.tics.2008.05.007

Summerfield, C., & de Lange, F. P. (2014). Expectation in perceptual decision making: Neural and computational mechanisms. *Nature Reviews Neuroscience, 15,* 745–756. http://dx.doi.org/10.1038/nrn3838

Ulrich, R., & Miller, J. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology, 38,* 816–827. http://dx.doi.org/10.1111/1469-8986.3850816

Woodman, G. F., Luck, S. J., & Schall, J. D. (2007). The role of working memory representations in the control of attention. *Cerebral Cortex, 17,* i118–i124. http://dx.doi.org/10.1093/cercor/bhm065

Wyart, V., Nobre, A. C., & Summerfield, C. (2012). Dissociable prior influences of signal probability and relevance on visual contrast sensitivity. *Proceedings of the National Academy of Sciences of the United States of America, 109,* 3593–3598. http://dx.doi.org/10.1073/pnas.1120118109

E-Mail Notification of Your Latest Issue Online!

Would you like to know when the next issue of your favorite APA journal will be available online? This service is now available to you. Sign up at https://my.apa.org/portal/alerts/ and you will be notified by e-mail when issues of interest to you become available!