

The Role of Color in Search Templates for Real-world Target Objects

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Abstract

■ During visual search, target representations (attentional templates) control the allocation of attention to template-matching objects. The activation of new attentional templates can be prompted by verbal or pictorial target specifications. We measured the N2pc component of the ERP as a temporal marker of attentional target selection to determine the role of color signals in search templates for real-world search target objects that are set up in response to word or picture cues. On each trial run, a word cue (e.g., “apple”) was followed by three search displays that contained the cued target object among three distractors. The selection of the first target was based on the word cue only, whereas selection of the two subsequent targets could be controlled by templates set up after the first visual presentation of the target (picture cue). In different trial runs, search displays either contained objects in their natural colors or monochromatic objects. These two display types were presented in different blocks (Experiment 1) or in random order within each block (Experiment 2). RTs were faster, and target

N2pc components emerged earlier for the second and third display of each trial run relative to the first display, demonstrating that pictures are more effective than word cues in guiding search. N2pc components were triggered more rapidly for targets in the second and third display in trial runs with colored displays. This demonstrates that when visual target attributes are fully specified by picture cues, the additional presence of color signals in target templates facilitates the speed with which attention is allocated to template-matching objects. No such selection benefits for colored targets were found when search templates were set up in response to word cues. Experiment 2 showed that color templates activated by word cues can even impair the attentional selection of noncolored targets. Results provide new insights into the status of color during the guidance of visual search for real-world target objects. Color is a powerful guiding feature when the precise visual properties of these objects are known but seems to be less important when search targets are specified by word cues. ■

INTRODUCTION

The selection of target objects in visual search tasks is controlled by representations of target-defining features in working memory (“attentional templates”; e.g., Duncan & Humphreys, 1989). Such search templates are activated before the start of a search process and facilitate the selection of targets among distractors by guiding attention toward the location of template-matching objects in the visual field (e.g., Eimer, 2014, 2015; Wolfe, 1994, 2007; Desimone & Duncan, 1995). When the identity of a particular target object is known in advance and attentional templates specify particular visual attributes of this object, some visual features appear to be more useful in guiding the deployment of attention than others (e.g., Wolfe & Horowitz, 2004). Color in particular appears to be an extremely powerful attribute for the guidance of attention during visual search (e.g., D’Zmura, 1991; Treisman & Gormican, 1988). For example, objects with a target-matching color will attract attention rapidly even when they are presented among a heterogeneous set of objects with different nontarget colors (e.g., Eimer, Kiss, Press, &

Sauter, 2009), demonstrating that search templates for specific colors are highly effective in guiding attention toward target locations. In most lab-based investigations of attentional guidance by search templates, the same target features or objects are repeated across many trials. Under such conditions, target selection can be controlled by a template that is rapidly established during the first few trials and then remains unchanged during the rest of the experiment. In the real world, observers rarely look for the same target object repetitively. Instead, new attentional templates for new target objects are activated at the start of each new selection episode. The goal of this study was to investigate the role of color during the formation of new attentional templates for real-world target objects.

Previous experiments that have studied the activation of new target templates have used cueing procedures where the identity of the target object in an upcoming search display was indicated by a cue stimulus that was presented at the start of each trial. In a study by Wolfe, Horowitz, Kenner, Hyle, and Vasan (2004), these target objects were specified either by picture or word cues, and the time interval between a cue and the subsequent search display was manipulated. Results demonstrated that search templates were set up more rapidly in response to

picture cues than word cues. The attentional selection of targets defined by word cues remained less efficient even when cues and target displays were separated by longer intervals (see also Schmidt & Zelinsky, 2009; Vickery, King, & Jiang, 2005; Wolfe, Butcher, Lee, & Hyle, 2003, for similar findings). These observations suggest that search templates that are set up after picture cues will represent the visual attributes of target objects more precisely than templates for targets that are specified by word cues. Because the template-guided selection of search targets is based on a match between these targets and a currently active search template, selection will be more efficient for templates that follow picture cues because these will usually provide a better match with the visual features of a target.

Given the importance of color for the guidance of visual search (Wolfe & Horowitz, 2004), color signals are likely to play a central role during the activation of new search templates. When search targets are specified by picture cues, these cues provide exact information about target colors, and this information is likely to increase the speed with which targets are selected among distractor objects in a subsequent search display. When the identity of an upcoming target is specified by a word cue, search templates may also include representations of the anticipated color of a target object, in particular for real-world objects that have a specific characteristic color (e.g., lemons; see Bramão, Reis, Petersson, & Faisca, 2011; Tanaka & Presnell, 1999, for such effects of color diagnosticity on object recognition). The role of color information during the formation of new target templates and the subsequent template-guided control of attentional target selection has not yet been studied systematically. In this study, we used electrophysiological measures to investigate how representations of color affect the speed of attentional target selection during visual search for new target objects that are specified by word cues or picture cues.

We used a paradigm that we previously developed to study the activation of new attentional templates for real-world target objects (Nako, Smith, & Eimer, 2015). In this earlier experiment, each trial run started with a word cue that specified the target object for this run. This word cue was followed by three successive search displays that all contained the cued target object among three different distractor objects. All objects appeared in their natural colors. With this cued trial run procedure, attentional guidance by search templates activated in response to word cues and picture cues could be assessed independently. The selection of target objects in the first search display of each trial run that immediately followed the word cue had to be based exclusively on information about expected target features provided by this cue. In contrast, the selection of targets in the second and third display followed the initial visual encounter with the target in the first display, which effectively served as a picture cue for these two subsequent selection episodes. In line with pre-

vious evidence that visual search performance is superior when target identity is specified by picture cues relative to word cues (Wolfe et al., 2004), RTs to targets in the second and third display of each trial run were about 250 msec faster than target RTs for the first search display that immediately followed the word cue.

To determine whether this RT benefit for search templates set up in response to picture cues was due to the faster allocation of spatial attention to target objects in the second and third display as compared with targets in the first display of each trial run, we recorded ERPs during task performance and measured the N2pc component in response to target objects separately for all three search displays within each trial run. The N2pc is a marker of attentional object selection that provides a temporally precise index of the deployment of spatial attention to targets among distractors in multistimulus visual search displays (e.g., Woodman & Luck, 1999; Eimer, 1996; Luck & Hillyard, 1994). When a target is presented in the left or right visual field, its attentional selection is reflected by an enhanced negativity at contralateral posterior electrodes (N2pc) that typically starts around 180–200 msec after stimulus onset and is generated in extrastriate areas of the ventral visual processing stream (Hopf et al., 2000). In our previous study (Nako et al., 2015), N2pc components to targets in the second and third display emerged earlier and were larger than N2pcs triggered by targets in the first display, demonstrating that the attentional selection of target objects is triggered more rapidly when these objects are specified by picture cues as compared with word cues. These N2pc onset differences between targets in the first display relative to targets in the second and third display were, however, smaller than the corresponding target RTs differences (30 msec vs. 250 msec), suggesting that, in addition to the speed of target selection, subsequent attentional processing stages responsible for the identification of target objects also operate more effectively when they are controlled by search templates that are set up in response to picture cues. There were no performance or N2pc differences between targets in the second and third display of each trial run, indicating that a single visual encounter with a target object is sufficient to establish an effective attentional template and that there are no additional benefits for the attentional selection of the same target in subsequent search episodes.

To rule out the possibility that N2pc differences between the first and subsequent presentations of target displays were primarily due to a generic template-unspecific facilitation of attentional allocation processes in situations where the same target object is selected for the second or third time, we ran a control experiment where word cues were replaced by picture cues that provided an exact match of the target object for each trial run (see Nako et al., 2015, for details). In this experiment, there were no longer any N2pc amplitude or onset latency differences between the first, second, and third search display of each trial run, demonstrating that, when a precise

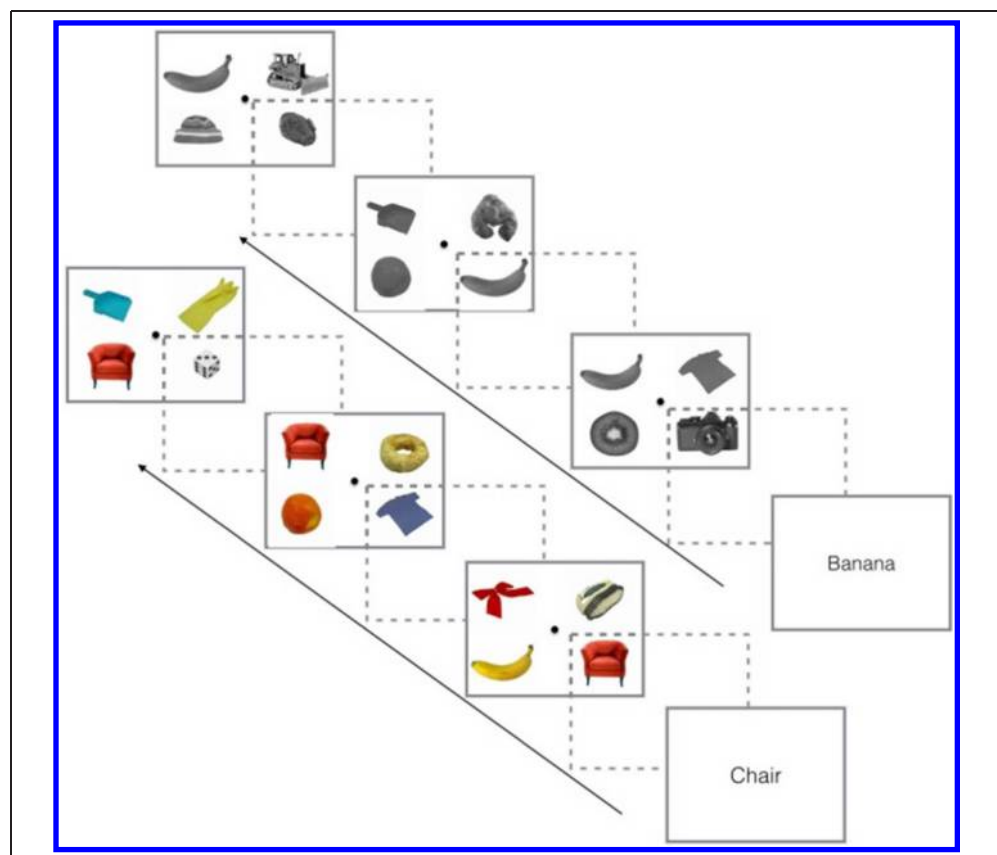
search template can already be activated before the first search display in each trial run, target selection operates efficiently for this display and shows no further improvement when the same target object is then selected again. Although there were no longer any N2pc differences, RTs in this control experiment were still faster for the second and third display relative to the first display in each trial run, indicating that performance benefits observed for target repetitions in successive search displays are primarily generated at stages that follow the template-guided selection of target objects.

The results of this previous N2pc study (Nako et al., 2015) have demonstrated the superiority of visual over verbal target specifications in the control of visual search. They suggest that search templates are visual representations that specify target features in an image-based analog fashion (e.g., Kosslyn & Thompson, 2003; Kosslyn, 1987) that will only be fully activated once a target object has been visually presented. The effectiveness of word cues in triggering useful search templates may also depend on which specific target object is indicated by such a cue. When a target object has canonical-invariant visual features (e.g., a banana), word cues may be able to elicit a relatively precise search template, resulting in faster attentional selection processes than for objects with more variable features. In line with this assumption, N2pc components to highly imageable target objects with canonical features in the first display immediately after a word cue

emerged earlier than N2pcs to less imageable objects, but still later than for target objects in the second and third display (Nako et al., 2015), indicating that picture cue benefits are present even for objects with invariant visual features.

Our previous N2pc study (Nako et al., 2015) has shown that relative to target templates set up in response to word cues, templates activated by picture cues will guide attention more rapidly to target objects in visual search displays. These findings raise the obvious question of which visual features or feature dimensions in attentional templates are responsible for these benefits. Given the dominant role of color signals during attentional guidance (Wolfe & Horowitz, 2004), it is possible that such benefits are primarily due to the fact that picture cues make it possible to activate precise representations of target colors, which can then be rapidly matched to particular objects in the subsequent search displays. This hypothesis can be tested by using similar procedures as in the study by Nako et al. (2015) and directly comparing the efficiency of picture versus word cues in one condition where all search display objects appear in their natural colors and another condition with monochromatic search displays that contain no color information at all (see Figure 1). In this study, word cues were again followed by three successive search displays on each trial run, and these search displays now either contained four colored objects or four

Figure 1. Examples of trial runs with colored or monochromatic search displays. At the start of each trial run, a word cue specified the target object for this run. The cue was followed by three successive search arrays that all contained the target object and three different distractor objects. Trial runs with colored or monochromatic displays were presented in different blocks in Experiment 1 and appeared in a random unpredictable order within each block in Experiment 2.



monochromatic objects. In Experiment 1, colored or monochromatic search displays were shown in separate blocks, so that participants knew in advance whether target and distractor objects would be colored or not. Different target objects were shown in each trial run, and these objects never appeared as distractors in other search displays. Two different sets of target and distractor images were shown in blocks with colored and monochromatic displays. Target objects appeared at an unpredictable location among three different distractor objects in each search display, and participants' task was to localize these targets.

We measured RTs and N2pc components to target objects in the first and the two subsequent displays of each trial run, separately for blocks with colored and monochromatic search displays. In blocks with colored displays, results were expected to confirm our previous observations (Nako et al., 2015), with slower RTs and delayed and attenuated N2pc components to targets in the first display relative to targets in the two subsequent displays, demonstrating the superiority of search templates activated in response to picture cues versus word cues. To assess the role of color signals in target templates set up to word cues or to picture cues, we compared N2pc components measured in blocks with colored displays to N2pc components in monochromatic blocks. Because the first presentation of a target object on each trial run serves as a picture cue, search templates that are activated after the first visual encounter with this target will provide a full visual representation of its features. Although this is the case regardless of whether target objects are colored or not, these templates do not include color information in monochromatic blocks. The comparison of N2pc components to targets in the second and third display of each trial run between blocks with colored and monochromatic displays will therefore reveal whether and to what degree the additional presence of color information in search templates that fully specify all target features facilitates the speed with which attention is allocated to target objects in search displays. The guidance of attention to targets in the first display of each trial has to rely exclusively on search templates activated by word cues. Any target N2pc differences between color and monochromatic blocks for the first display will therefore provide evidence that anticipated target colors are also included in these templates. For example, attention may be allocated more rapidly to target objects in the first display in color blocks as compared with monochromatic blocks where search cannot be guided by color, resulting in earlier N2pc onsets in color blocks. Alternatively, such N2pc onset differences between color and monochromatic blocks could also be due to representations of target color being activated by default in response to word cues and interfering with the template-guided selection of target objects in monochromatic blocks that is based on other target attributes such as their expected shape.

EXPERIMENT 1

Methods

Participants

Seventeen paid volunteers participated in this experiment. Two of them were excluded because their mean RTs exceeded 1000 msec, and three others had to be removed because of excessive eye movements during task performance, resulting in an insufficient number of trials for EEG averaging. The remaining 12 participants ($M = 26.25$ years, $SD = 6.2$, range = 20–40 years, five women) had normal or corrected vision, and all were native English speakers.

Stimuli, Design, and Procedure

Experimental procedures were very similar to those employed in our previous study (Nako et al., 2015), except that the objects in the search displays now appeared either in color or as monochromatic images. Stimuli were 320 color photographs of real-world objects that were selected from the Boss normalized stimuli set (Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010) and the Object Databank (Center for the Neural Basis of Cognition, Carnegie Mellon University). Each image subtended $1.72^\circ \times 1.72^\circ$. Monochromatic images were generated by converting the original colored images with the black and white image adjustment tool in Adobe Photoshop. The full set of objects was randomly divided into two groups of 160 objects. For half of all participants, objects in one group served as targets and objects in the other group as distractors, while this assignment was reversed for the remaining participants. Eighty target objects and 80 distractor images appeared in blocks where all objects in the search displays were colored. The other 80 target and 80 distractor images were shown in different blocks that contained only monochromatic search displays.

All stimuli were presented on a 24-in. LCD monitor with a 100-Hz refresh rate at a viewing distance of 100 cm against a white background. On each trial run, three consecutive search displays were presented. Search displays contained the target object for this trial run together with three different nontarget objects. Each of these four objects appeared in one quadrant of the visual field at an eccentricity of 2° from central fixation. The first search display was preceded by a word cue that specified the target object for this trial run. This cue display was presented for 1600 msec. At 1000 msec after the offset of the cue display, the first of the three successive search displays was presented (as illustrated in Figure 1). Search displays remained visible until a response was recorded. The interval between the offset of a search display and the onset of the next display in the same trial run was 1000 msec. The interval between the offset of the third search display in a trial run and the onset of the cue display on the next trial was 1600 msec. A central fixation point was continuously

present, and participants were instructed to maintain central fixation throughout each experimental block. Each target object was used only on one trial run for each participant, and its position within each search display was randomly assigned. Participants' task was to detect the target object that was specified by the word cue for a given trial run and to indicate its vertical location in the search display with a corresponding key press. They responded by pressing the computer keyboard keys "1" or "0" (which are arranged vertically) with their right or left index finger to signal the presence of a target in the upper versus lower visual field.

The experiment included four successive blocks where all search displays contained colored objects and four other successive blocks where these displays contained monochromatic objects. The order in which these color and monochromatic blocks were delivered was counter-balanced between participants. Each block included 20 trial runs where a cue display was followed by three successive search displays. Participant therefore searched for 80 different colored target objects among colored distractors in the color blocks and for 80 different monochromatic targets among distractors in the monochromatic blocks.

EEG Recording and Data Analysis

EEG was DC-recorded from 23 scalp electrodes at standard positions of the extended 10/20 system (500 Hz sampling rate; 40 Hz low-pass filter) against a left-earlobe reference and re-referenced offline to averaged earlobes. The continuous EEG was segmented from -100 to 500 msec relative to the onset of a particular search display, separately for all three displays in a trial run. Trials with artifacts (horizontal

EOG exceeding $\pm 25 \mu\text{V}$, vertical EOG exceeding $\pm 40 \mu\text{V}$, all other channels exceeding $\pm 80 \mu\text{V}$) were removed before analysis. Averaged waveforms for trials with correct responses were computed for all three displays in a given trial run, relative to a 100-msec prestimulus baseline. Different averages were generated for search displays with targets on the left or right side, separately for blocks with colored and monochromatic search displays. N2pc amplitudes were quantified on the basis of ERP mean amplitudes obtained between 200 and 300 msec after search array onset at lateral posterior electrodes PO7 and PO8 and were analyzed with repeated-measures ANOVAs, with Greenhouse-Geisser corrections applied when appropriate. Target N2pc onset latencies were determined by using the jackknife-based analysis method described by Miller, Patterson, and Ulrich (1998) and Ulrich and Miller (2001), with an absolute threshold criterion of $-1 \mu\text{V}$ and F and t values corrected according to the formulas described by these authors. For pairwise comparisons of N2pc latencies between conditions, additional Bonferroni corrections were applied where appropriate.

Results

Behavioral Performance

Figure 2 (left) shows mean RTs on trials with correct responses, for the first, second, and third display in each trial run, displayed separately for blocks with monochromatic or colored search displays. In a within-subject ANOVA with the factors Serial position (first, second, or third display) and Display type (monochromatic vs. colored), there were main effects of Serial position, $F(2, 22) = 113.27, p < .001, \eta^2 = .911$, reflecting slower RTs for the first display within

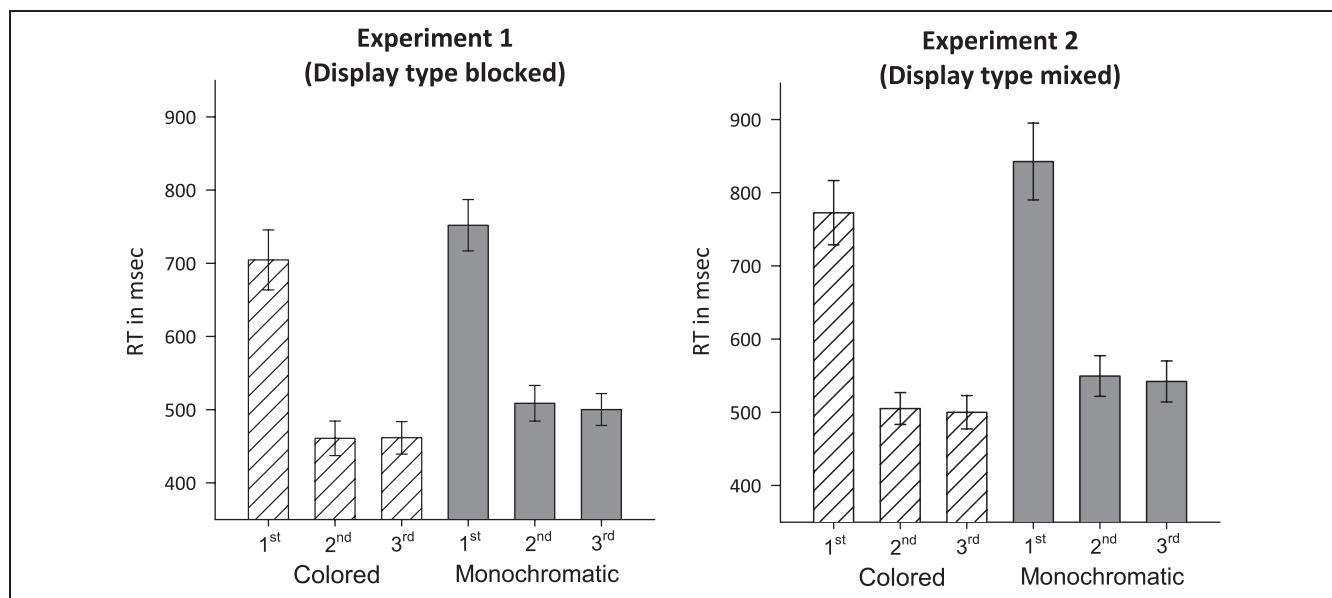


Figure 2. Mean RTs on trials with correct responses to targets in the first, second, and third search display of each trial run in Experiment 1 (blocked presentation or colored and monochromatic displays) and Experiment 2 (mixed presentation of display types). RTs are shown separately for colored and monochromatic search displays. Error bars represent $\pm 2 \text{ SEM}$.

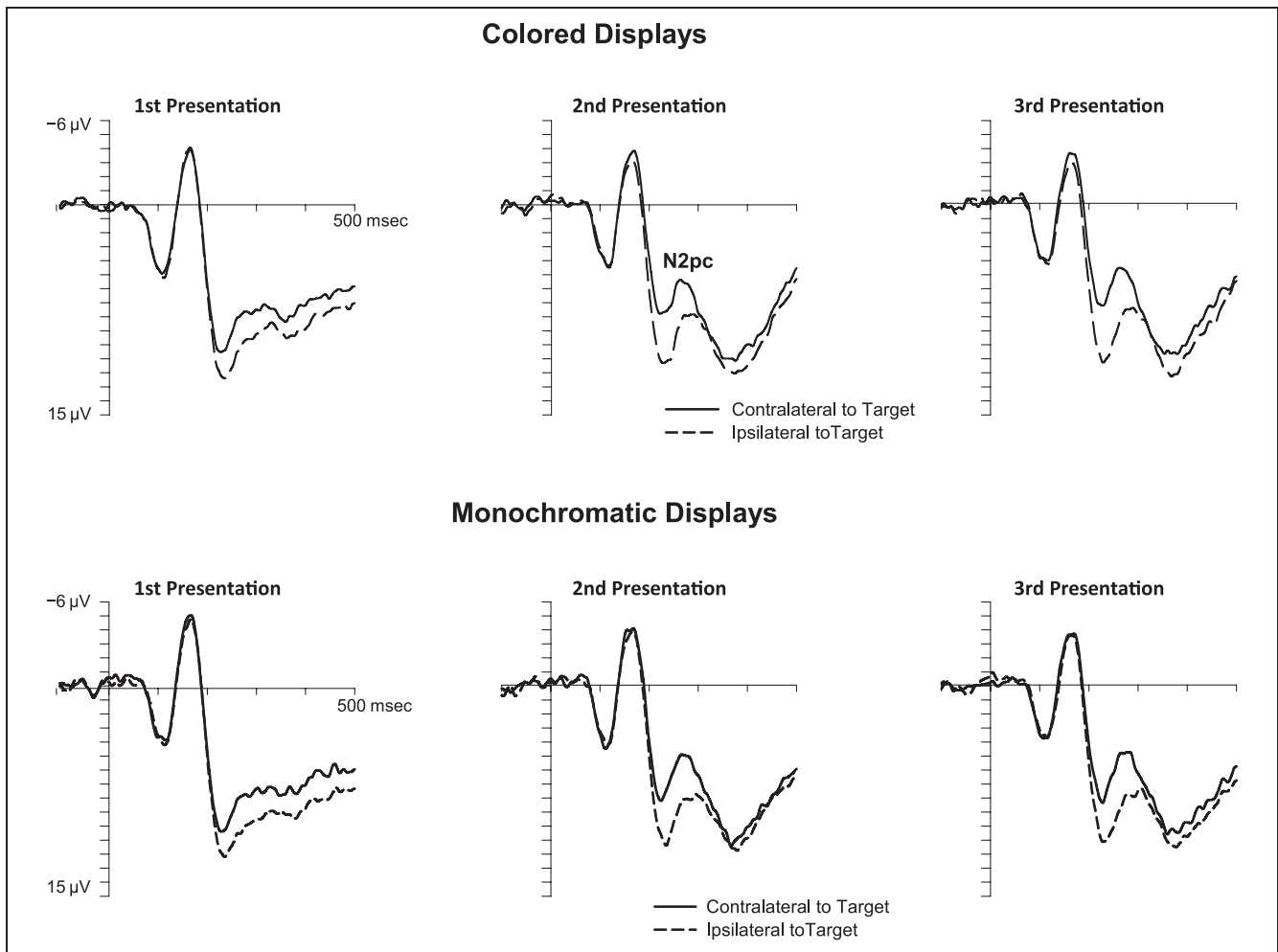


Figure 3. Grand-averaged ERP waveforms elicited in Experiment 1 in response to targets in the first, second, and third display in each trial run at posterior electrodes PO7/8 contralateral and ipsilateral to a target object, shown separately for blocks with colored search displays (top) and monochromatic displays (bottom).

each trial run, and Display type, $F(2, 22) = 11.25, p = .006, \eta^2 = .506$, with slower RTs in blocks with monochromatic displays relative to blocks with colored displays (587 msec vs. 543 msec, averaged across all three display positions). There was no interaction between these two factors, $F(2, 22) < 1$, demonstrating that the RT cost for monochromatic as compared with colored search displays did not differ between the three search displays within a trial run. RTs to target objects in the first display were delayed by nearly 250 msec relative to the second and third display in each display run, both for blocks with colored displays (704 msec vs. 463 and 462 msec, respectively), and for blocks with monochromatic displays (752 msec vs. 508 and 502 msec, all $ps < .001$). There were no reliable RT differences between the second and third display in each trial run for either display type, both $t(11) < 1.9$. Response accuracy was high (95% across all conditions) and did not differ between the first, second, and third display within each trial run, $F(2, 22) < 1$. There was a main effect of display type on accuracy, $F(1, 11) = 6.106, p = .031, \eta^2 = .357$, reflecting a small but systematic benefit for blocks

with colored as compared with monochromatic search displays (96.4% vs. 94.9% correct responses). No interaction between serial position and display type was present for accuracy, $F(2, 22) < 1$.

N2pc Components

Figure 3 shows ERPs triggered in the 500-msec interval after search display onset at electrodes PO7/8 contralateral and ipsilateral to the target object in the search display. ERP waveforms are displayed for each of the three successive displays in each trial run and are shown separately for blocks with monochromatic search displays (top) and colored search displays (bottom). Clear target N2pc components were elicited in response to all search displays. To highlight N2pc differences between the first and successive target presentations on each trial run and between colored and monochromatic displays, Figure 4 shows N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. N2pc components were delayed and attenuated in response to targets in the

first display in each trial run (solid lines) relative to targets in the two subsequent displays (dashed lines). The N2pc elicited by the first search display was very similar in blocks with colored and monochromatic stimuli. In contrast, the N2pc to targets in the second and third display appears to emerge earlier for colored as compared with monochromatic displays.

These informal observations were confirmed by statistical analyses of N2pc mean amplitudes and onset latencies. A repeated-measures ANOVA on ERP mean amplitudes measured at PO7/8 in the N2pc time window (200–300 msec poststimulus) with the factors Serial position, Display type, and Laterality (electrode contralateral vs. ipsilateral to the target) revealed a main effect of Laterality, $F(1, 11) = 30.52, p < .001, \eta^2 = .735$, reflecting the presence of reliable N2pc components. An interaction between Serial position and Laterality, $F(2, 22) = 8.52, p = .002, \eta^2 = .436$, confirmed that N2pc components were attenuated for the first target display in each trial run. However, comparisons of contralateral and ipsilateral ERPs confirmed that reliable N2pc components to targets in colored or monochromatic search displays were present not only for the second and third display in each trial run, all $t(11) > 4.5$, all $ps < .001$, but also for the first display, both $t(11) > 3.9$, both $ps < .005$. There were no N2pc amplitude differences between targets in the second and third search display for either display type, both $t(11) < 1.2$. There was no interaction between display type and laterality and no three-way interaction between serial position, display type, and laterality, both $Fs < 1$, demonstrating that N2pc amplitudes did not differ between blocks with colored and monochromatic targets.

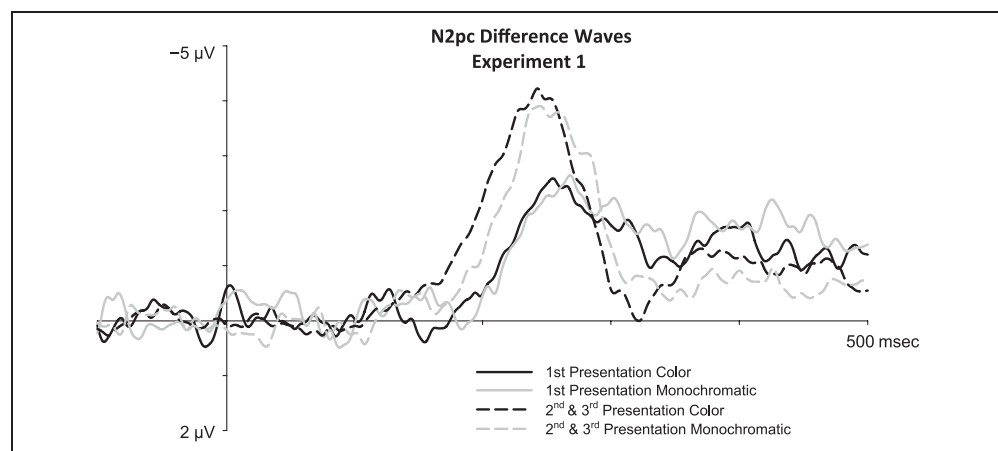
N2pc onset latencies, as determined with a jackknife-based procedure (Ulrich & Miller, 2001; Miller et al., 1998) were analyzed in two ANOVAs with the factors Serial position for blocks with colored and monochromatic displays, respectively. Significant effects of Serial position were present for both displays types, $F_c(2, 22) = 5.34, p = .013$ and $F_m(2, 22) = 7.05, p = .004$, respectively, reflecting the fact that the target N2pc emerged later for the first display in each trial run relative to the second

and third display. Because there were no reliable N2pc onset latency differences between the second and third display in each run for either colored displays (175 and 174 msec poststimulus) or monochromatic displays (200 and 192 msec poststimulus; both $ps > .05$), N2pc difference waveforms were averaged across the second and third display (as shown in Figure 4) and then compared with the N2pc to targets in the first display. For blocks with colored displays, the N2pc onset to targets in the first display was delayed relative to the N2pc to targets in the second and third display (213 vs. 175 msec poststimulus; $t_c(11) = 3.88; p < .05$). An analogous N2pc delay for targets in the first display relative to targets in the two subsequent displays was also observed for blocks with monochromatic displays (216 msec vs. 196 msec; $t_m(11) = 2.28; p < .05$). To assess whether targets were selected more rapidly in colored as compared with monochromatic displays, N2pc onset latencies were compared between these two display types, separately for targets in the first display of each trial run and targets in the two subsequent displays (averaged across the second and third display). There was no N2pc latency difference for targets in the first display between blocks with colored and monochromatic displays (213 msec vs. 216 msec; $t_c < 1$). In contrast, the N2pc to targets in the two subsequent displays emerged significantly earlier in blocks with colored displays relative to blocks with monochromatic displays (175 msec vs. 196 msec; $t_c(11) = 2.9, p < .05$).

Discussion of Experiment 1

The goal of Experiment 1 was to find out whether the availability of color signals facilitates the speed of attentional target selection processes when these processes are guided by new attentional templates that are set up in response to picture or word cues. The behavioral and N2pc results observed in the color blocks of Experiment 1 confirm the findings from our previous study (Nako et al., 2015). RTs were delayed by about 250 msec for targets in the first display as compared with targets in the two subsequent displays, and the target N2pc emerged

Figure 4. N2pc difference waveforms obtained in Experiment 1 by subtracting ipsilateral from contralateral ERPs at PO7/8. N2pc waveforms are shown for first target in each trial run and for the second and third target in each run (averaged across these two targets), separately for blocks with colored or monochromatic search displays.



later and was attenuated for the first display within each trial run. These observations demonstrate that the attentional selection of target objects is delayed when targets are specified by word cues relative to a situation where search templates can be based on a previous encounter with a visual image of the target. As in our earlier study, the N2pc onset latency difference between the first and the two subsequent targets was smaller than the corresponding RT difference, demonstrating that processing stages beyond the initial spatial selection of target objects contribute to the performance costs for search guided by word cues relative to picture cues. In blocks with monochromatic search displays, RTs and N2pc components were also delayed for the first presentation of a target in a trial run relative to its second and third presentation, demonstrating the superiority of picture over word cues under conditions where color information is not available to guide attentional target selection.

Experiment 1 demonstrated that search templates set up in response to picture cues (i.e., the first presentation of a target object in each trial run) guide the subsequent allocation of attention more effectively when these templates include representations of target color. N2pc components to targets in the second and third display of each trial run emerged 21 msec later in monochromatic blocks relative to color blocks (see Figure 4). This is an important observation, because the attentional selection of these targets could always be controlled by a search template that fully specified the featural properties of the current target object, regardless of whether displays contained color information or not. The fact that target N2pc components were still triggered more rapidly in color blocks therefore provides direct evidence that the presence versus absence of color signals affects the speed of attentional target selection even when all visual properties of target objects are fully known in advance. The availability of such signals in colored displays may have facilitated the speed with which a match between search templates and target objects was detected. In addition, because color information was absent in monochromatic search displays, fewer features were available to discriminate between target and distractor objects, and this may have resulted in a delayed allocation of attention to targets.

Although the earlier emergence of N2pc components to targets in the second and third display in color versus monochromatic blocks provides new evidence for the effects of color representations in new target templates that are set up in response to picture cues, no such N2pc latency differences were found for target objects that immediately followed the word cue in the first search display of each trial run. This observation could suggest that, for search templates that are set up in response to word cues, representations of target color have no effect on the speed with which attention is allocated to target objects. RTs to targets in the first display were faster in color relative to monochromatic blocks. However, the fact that this RT benefit for color blocks did not increase for targets

in the second and third display (which were selected faster in color blocks) suggests that it does not directly reflect differences in the rapid allocation of attention to target objects, but instead the facilitation of subsequent recognition-related processes. Matching attentional templates to visual representations of selected objects during their recognition is likely to be more efficient when color provides an additional dimension on which such a match can be registered.

If search templates that are set up in response to word cues always include information about target color by default, the absence of any N2pc differences between color and monochromatic blocks for the first target in each trial run is surprising. Color templates would be expected to facilitate the selection of targets with template-matching colors and to impair the selection of monochromatic target objects. The apparent absence of such color-related costs or benefits may indicate that observers did not activate color search templates in response to word cues by default in Experiment 1. Because colored and monochromatic search displays were presented in separate blocks, participants always knew in advance whether or not target objects would be colored. For this reason, the target templates set up to word cues may not have included any color information in monochromatic blocks. This was tested in Experiment 2, where trial runs with colored or monochromatic search displays appeared randomly and unpredictably within each block.

EXPERIMENT 2

In Experiment 1, N2pc components to targets in the first search display did not differ between colored and monochromatic blocks. Because display color was fully predictable, participants may have chosen not to activate color target templates in monochromatic blocks. In Experiment 2, all blocks contained an equal number of trial runs with colored or monochromatic displays, and these were presented in an unpredictable random order. In each trial run, all three search displays were either colored or monochromatic. If the search templates that are activated in response to word cues represent anticipated target colors under these conditions, N2pc differences between colored and monochromatic search displays should now already be evident for the first display within each trial run. For targets in the second and third display, N2pc components should again emerge earlier for trial runs with colored search displays, confirming the benefits on the speed of target selection provided by color templates set up in response to picture cues.

Methods

Participants

Twelve paid volunteers ($M = 28.00$ years, $SD = 6.26$, range = 20–52 years, six women) took part in Experiment 2. All

participants had normal or corrected vision, and all were native English speakers. None of them had participated in Experiment 1.

Stimuli, Design, Procedure, EEG Recording, and Data Analysis

These were identical to Experiment 1, with the exception that trial runs with colored and monochromatic search displays now appeared unpredictably and with equal probability within the experiment. Experiment 2 included eight blocks, with 20 trial runs in each block. Because display type (colored vs. monochromatic) was determined randomly for each new trial run, word cues that specified the target object for a given trial run contained no information about whether target and distractor objects would be colored or not. Within each trial run, display type remained constant (i.e., there were always three successive colored displays or three monochromatic displays).

Results

Behavioral Performance

Figure 2 (right) shows mean RTs on trials with correct responses, separately for the first, second, and third display in each trial run and for trials with monochromatic or colored search displays. Analogous to Experiment 1, an ANOVA revealed main effects of Serial position, $F(2, 22) = 118.7, p < .001, \eta^2 = .915$, for RTs. RTs to target objects in the first display were again delayed relative to targets in the second and third display. This was the case both for trial runs with colored displays (773 msec vs. 505 and 500 msec, respectively) and for trial runs with monochromatic displays (843 msec vs. 550 and 542 msec, all $ps < .001$). There were no reliable RT difference between the second and third displays in each trial run for either display type, both $t(11) < 1.3$. There was also a main effect of Display type, $F(2, 22) = 25.5, p < .001, \eta^2 = .699$, as RTs were faster on trial runs with colored displays than on trial runs with monochromatic displays. Importantly, and in contrast to Experiment 1, a significant interaction between serial position and display type was present, $F(2, 22) = 5.4, p = .012, \eta^2 = .330$. This was due to the fact that the RT costs observed for monochromatic as compared with colored search displays were more pronounced for the first search display (70 msec) than for the second and third display (45 and 42 msec, respectively) within each trial run.

Response accuracy was 97% across all conditions and did not differ between the first, second, and third display within each trial run, $F(2, 22) < 1$. There was a main effect of Display type, $F(1, 11) = 6.95, p = .023, \eta^2 = .387$, because of the fact that accuracy was slightly higher on trial runs with colored as compared with monochromatic search displays (97.5% vs. 96.8%). No interaction

between Serial position and Display type was found for accuracy, $F(2, 22) < 1$.

N2pc Component

Figure 5 shows ERPs triggered at electrodes PO7/8 contralateral and ipsilateral to the search target for each display in a trial run, separately for runs with colored and monochromatic search displays. Clear target N2pc components were elicited in response to all search displays. N2pc amplitude and latency differences are illustrated in the N2pc difference waveforms shown in Figure 6 for trial runs with colored and monochrome search displays, separately for the first display and the two subsequent displays in each trial run. As in Experiment 1, N2pc components were delayed and attenuated in response to targets in the first display, and the N2pc to targets in the second and third display emerged later for monochromatic as compared with colored displays. In contrast to Experiment 1, this N2pc onset delay for monochromatic displays was now already apparent for the first display in each trial run.

Statistical analyses of N2pc mean amplitudes and onset latencies confirmed these observations. A repeated-measures ANOVA on ERP mean amplitudes measured at PO7/8 in the N2pc time window (200–300 msec post-stimulus) with the factors Serial position, Display type, and laterality revealed a main effect of Laterality, $F(1, 11) = 48.76, p < .001, \eta^2 = .816$, confirming the presence of reliable N2pc components. As in Experiment 1, there was an interaction between Serial position and Laterality $F(2, 22) = 19.38, p = .002, \eta^2 = .638$, due to the fact that N2pc components were attenuated for the first display as compared with the two subsequent displays in each trial run. Comparisons of contralateral and ipsilateral ERPs confirmed that reliable N2pc components to targets in colored or monochromatic search displays were present not only for the second and third display in each trial run, all $t(11) > 5.9$, all $ps < .001$, but also for the first display, both $t(11) > 3.2$, both $ps < .01$. N2pc amplitudes did not differ between targets in the second and third search display for either display type, both $t(11) < 1$. There was no interaction between Display type and Laterality and no three-way interaction between Serial position, Display type, and Laterality, both $Fs < 1.87$, indicating that N2pc amplitudes did not differ reliably between colored and monochromatic targets.

N2pc onset latencies were again determined with a jackknife-based procedure (Ulrich & Miller, 2001; Miller et al., 1998). Two ANOVAs with the factors Serial position conducted for trial runs with colored and monochromatic displays revealed significant effects of Serial position for both displays types, $F_c(2, 22) = 7.28, p = .004$, and $F_m(2, 22) = 8.52, p = .002$, respectively. As in Experiment 1, these effects were due to the fact that the target N2pc was delayed for the first display in each trial run relative to the second and third display. Comparisons

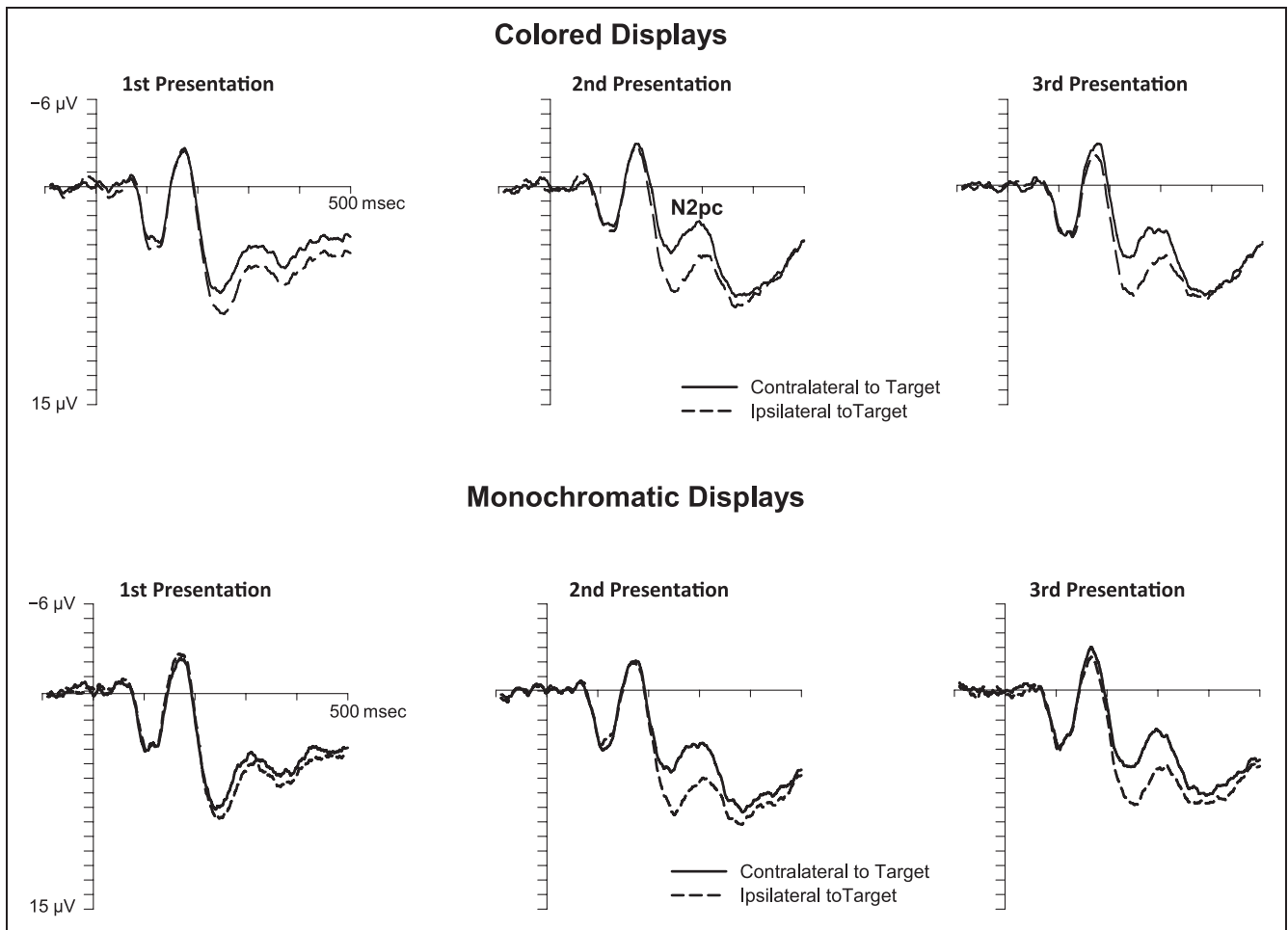
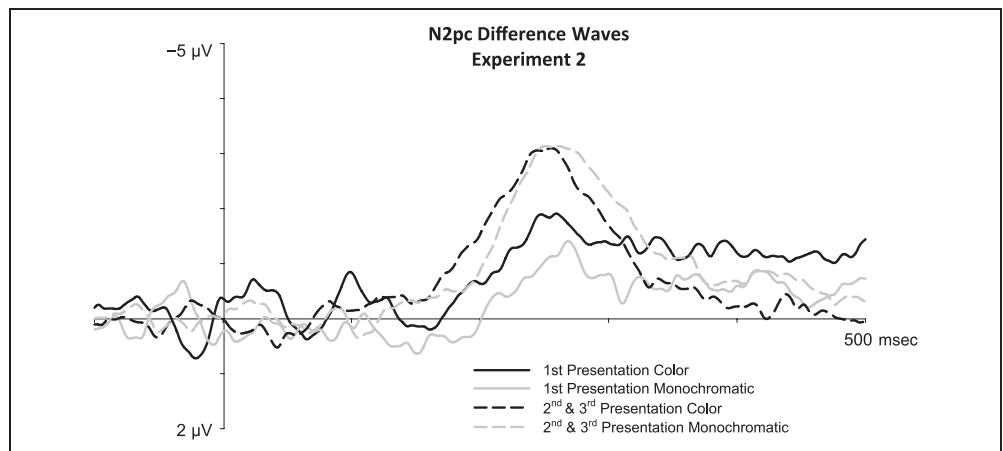


Figure 5. Grand-averaged ERP waveforms elicited in Experiment 2 in response to targets in the first, second, and third display in each trial run at electrodes PO7/8 contralateral and ipsilateral to a target object, measured on trial runs with colored search displays (top) and monochromatic displays (bottom).

of N2pc onset latencies between serial display positions confirmed this conclusion. Because there were no reliable N2pc onset latency differences between the second and third display in each run for either colored or monochromatic displays, both $ps > .05$, N2pc difference waveforms were averaged across the second and third display

(as shown in Figure 6). For colored displays, the N2pc to targets in the first display was delayed relative to the N2pc to targets in the second and third display (217 msec vs. 180 msec; $t_c(11) > 2.69$; $p < .05$). A reliable N2pc onset difference between targets in the first display and targets in the two subsequent displays was also observed for

Figure 6. N2pc difference waveforms obtained in Experiment 2 by subtracting ipsilateral from contralateral ERPs at PO7/8. N2pc waveforms are shown for first target in each trial run and for the second and third target in each run (averaged across these two targets), separately for trial runs with colored or monochromatic search displays.



monochromatic displays (249 msec vs. 203 msec; $t_c(11) = 2.86$; $p < .05$). As in Experiment 1, differences in target selection speed between colored and monochromatic displays were assessed by comparing N2pc onset latencies between these two display types, separately for targets in the first display and in the two subsequent displays of each trial run. N2pc components to targets in the second and third displays emerged reliably earlier when these displays contained colored objects relative to monochromatic displays (180 msec vs. 203 msec; $t_c(11) = 3.88$, $p < .05$), analogous to the findings of Experiment 1. Importantly, and in contrast to Experiment 1, a significant target N2pc onset delay for monochrome as compared with colored displays was now also present for the first display within each trial run (217 msec vs. 249 msec; $t_c(11) = 2.27$, $p < .05$).

Discussion of Experiment 2

In Experiment 2, trial runs with colored and monochromatic search displays were presented in random order, so that participants could not predict at the start of each trial run whether the upcoming displays would contain a colored target object or not. As in Experiment 1, target RTs were much slower for the first display in each trial run relative to the two subsequent displays, and N2pc components were attenuated and delayed in response to targets in the first display as compared with targets in the other two displays, reflecting the general benefits of picture cues over word cues. The N2pc to target objects in the second and third display was again delayed by 23 msec for monochromatic as compared with colored search displays, confirming that the inclusion of color information in new attentional templates that are set up in response to picture cues expedites the speed of attentional target selection processes.

The main difference with Experiment 1 was that N2pc components to target objects in the first display now also emerged reliably later for monochromatic as compared with colored search displays (see Figure 6). This suggests that, when the presence or absence of color information in an upcoming search display was unpredictable, participants activated search templates that included the anticipated color of the target in response to word cues. The delayed onset of N2pc components to targets in monochromatic search displays in Experiment 2 is likely to reflect the costs of such color templates. The presence of color signals in target templates may result in a mismatch with monochromatic targets during their template-guided selection and may also interfere with the control of attention by other target attributes, thereby delaying the allocation of attention to target objects in monochromatic blocks. The observation that the RT costs for monochromatic targets versus colored targets were larger for the first target in each trial run than for the two subsequent targets in Experiment 2 provides further support for the hypothesis that color templates activated by word cues

impair the selection of noncolored target objects. Overall, these behavioral and N2pc differences between colored and monochromatic targets that immediately followed a word cue suggest that, when these two types of targets are unpredictable, search templates for target colors are activated by default, resulting in costs for attentional selection when monochromatic targets are encountered. The absence of such selection costs for monochromatic target objects in Experiment 1 indicates that, when observers know that only such targets will be encountered, color representations play no role in target templates that are activated by word cues. This will be further considered below.

GENERAL DISCUSSION

In this study, we assessed the role of color signals in the guidance of attentional target selection by search templates for new target objects. Do color signals facilitate the speed with which attention is allocated to these objects, even when a target object has already been seen during a previous selection episode, and target templates include a full visual representation of its properties? Do search templates that are set up in response to word cues also include representations of anticipated target colors? To answer these questions, we employed procedures similar to those used in a previous study (Nako et al., 2015). On each trial run, three successive search displays containing the target object and three nontarget distractors were preceded by a word cue that specified the target for this trial run. The three search displays in each trial run were either colored or monochromatic. In Experiment 1, these two types of displays were presented in different blocks. In Experiment 2, trial runs with colored or monochromatic search displays appeared in random order in each block, so that participants could not predict the presence or absence of color information in the first display after the word cue.

As in our previous study (Nako et al., 2015), RTs were much slower and N2pc components were attenuated and delayed when targets appeared immediately after the word cue in the first display of each trial run relative to targets in the second and third display. This was the case both for trial runs with colored and monochromatic displays and confirms the supremacy of picture cues over word cues in the template-guided control of visual search (see also Vickery et al., 2005; Wolfe et al., 2003, 2004). Once a search target has been presented, a complete visual representation of its features can be activated, and the allocation of attention to this target can be based on a full match with the visual properties of the search template. Because word cues usually only provide a limited amount of information about the likely visual attributes of a specific target object, search templates that are set up in response to word cues will guide target selection less efficiently than templates activated by picture cues. As the attentional benefits for picture over word

cues are a direct consequence of the fact that picture cues enable the activation of more precise target templates, no such benefits should be found under conditions where this is not the case. For example, picture cues that only provide information about the category of upcoming target objects should not be superior to word cues, especially when individual target objects vary in their visual properties. Conversely, word cues may be highly effective in guiding attention when they have previously been associated with a particular visual object and therefore provide detailed information about the features of this object. These predictions can be tested in future N2pc experiments where the specificity of the visual information provided by picture and word cues is manipulated independently.

Because the first presentation of a target object in each trial run serves as a picture cue for search templates that are used in the two subsequent selection episodes, these templates will always include a complete visual representation of target features, regardless of whether targets appear in their own natural colors or in monochromatic displays. The current study provided clear-cut evidence that color information facilitates the guidance of attention by search templates that are set up in response to picture cues. In both experiments, the attentional selection of targets in the second and third display was faster in trial runs with colored as compared with monochromatic search displays, as reflected by an earlier onset of target N2pc components. The size of these color benefits on N2pc onset latencies on trial runs with colored search displays was very similar in both experiments (21 msec vs. 23 msec), demonstrating that color information facilitates the speed with which attention is allocated to known real-world search target objects in a highly systematic and replicable fashion. The corresponding RT benefits for colored as compared with monochromatic targets in the second and third display in each trial run were larger (approximately 45 msec), suggesting that the presence of color signals in search templates also facilitates attentional processing at stages that follow the initial allocation of target objects, such as object identification processes that are based on a comparison between the visual features of selected objects and stored target templates.

On trial runs with colored search displays, the onset of the N2pc to targets in the second and third display overlapped with the N1 component, resulting in an enhanced contralateral negativity during the peak and descending flank of the N1. This early onset of the contralateral N2pc during the N1 time window, which can be seen in Figures 3 and 5, was very similar to the pattern of N2pc results found in our previous study with colored displays (Nako et al., 2015). Previous studies that employed other types of stimuli and attentional manipulations (e.g., Eimer & Grubert, 2014; Eimer et al., 2009; McDonald, Hickey, Green, & Whitman, 2009) have also found that when target objects are defined by a known

feature such as a particular color, target N2pc components already emerge at latencies of approximately 170–180 msec poststimulus and therefore overlap with N1 components in ERP waveforms. The presence of such early-onset N2pcs is generally interpreted as evidence that attention is allocated rapidly and effectively to target objects when these objects precisely match a currently active search template.

To determine the role of color signals in search templates that are activated in response to word cues, before the first visual encounter with a target object, we compared N2pc components to targets in the first display of each trial run when this display was either colored or monochromatic. If search templates set up by word cues include representations of target color, this could give rise to benefits for the selection of targets in colored displays and/or costs for target selection in monochromatic displays. Benefits should occur when target selection can be guided by a color match with the search template, whereas costs could be the consequence of a mismatch between a color template and a monochromatic search target. In Experiment 1, N2pc components to targets in the first display did not differ between blocks with colored and monochromatic displays, suggesting that there were neither color-related costs nor benefits for the speed of attentional allocation to target objects defined by word cues. The apparent absence of any color template costs for the selection of monochromatic targets in Experiment 1 could have been due to the fact that colored and monochromatic search displays were presented in separate blocks, which may have led participants to set up search templates that did not include target color in monochromatic blocks. To test this, trial runs with colored or monochromatic displays appeared unpredictably within blocks in Experiment 2. Under these conditions, N2pc components to targets in the first display were delayed for monochromatic versus colored search displays, and there were also additional costs for RTs to targets in monochromatic displays. This suggests that the search templates that were activated in response to word cues in Experiment 2 did indeed include information about target color and that this resulted in costs for the speed of deploying attention to monochromatic targets. The exact nature of these costs will need to be specified in future studies. One possibility is that attentional guidance by target features other than color (such as object shapes) in monochromatic search displays operates less effectively when search templates also represent target colors. It is also possible that the presence of color representations in search templates triggered a mismatch between the expected color of a target object and its actual achromatic surface features that delayed the allocation of attention to this object.

A surprising outcome of the current study was that we found no evidence that representations of anticipated target colors in search templates set up in response to word cues produce benefits for the selection of colored

target objects. If the target templates activated by word cues in Experiment 1 included color signals only in color blocks but not in monochromatic blocks, the availability of color as an additional guiding feature should have facilitated the allocation of attention to color-matching target objects, resulting in earlier N2pc components to these targets. To account for the apparent absence of such color benefits, it is important to consider the fact that the ability of word cues to trigger useful search templates is likely to vary considerably between different objects. For objects with canonical features, a verbal description may be sufficient to form target templates that match some of their perceptual attributes. For target objects with variable features, a visually precise target-matching attentional template cannot be activated in response to word cues, resulting in less efficient visual search performance. Such object-specific differences were demonstrated by Castelano, Pollatsek, and Cave (2008) in an eye-tracking study where search displays contained real-world target objects that were either typical or atypical exemplars of a particular object category. When target identity was specified by word cues, RTs were faster to typical than to atypical targets (see also Nako et al., 2015, for evidence that N2pc components to target objects specified by word cues are triggered earlier for highly imageable vs. less imageable objects), whereas no such typicality effects were present when targets were defined by picture cues.

There may also be systematic differences between individual objects with respect to the ability of word cues to activate specific target color representations. When a particular color is a diagnostic feature for a specific object or object class (e.g., Bramão et al., 2011; Tanaka & Presnell, 1999), a verbal label (e.g., “lemon”) may be sufficient to activate an attentional template that includes the canonical color of the target. For such target objects, word cues could in principle facilitate relatively rapid color-based selection processes, resulting in early-onset N2pc components when these targets appear in colored search displays. There is however a major methodological difficulty in isolating such color-specific attentional selection benefits with naturalistic visual objects. There are only few real-world objects that have a canonical color without also having other diagnostic visual attributes, such as a characteristic shape. The majority of objects with a diagnostic color belong to natural categories where exemplars are typically characterized by strong associations between a particular color and a specific shape. For example, in our stimulus set of 320 objects, there were approximately 50 items that could be classified as having a specific canonical color. All of these were either fruit or vegetables, and all also had a canonical shape.¹ The absence of any N2pc differences to targets in the first display between color and monochromatic blocks in Experiment 1 may therefore reflect the fact that even though color-based attentional guidance was possible for the relatively small subset of objects with canonical colors, an alternative shape-based selection strategy was readily

available for these objects. Because shape information was equally present in colored and monochromatic displays, attentional guidance by shape may have been similarly efficient for both types of displays.

In short, the absence of color-specific attentional selection benefits for N2pc components to real-world targets specified by word cues in this study may be linked both to the relatively small number of objects with canonical colors and to the fact that these objects also had a characteristic shape. If color information in target templates set up to word cues cannot facilitate the speed of attentional guidance processes, why would observers opt to represent the expected colors of cued target objects at all? As mentioned earlier, target templates are not only involved in the rapid allocation of spatial attention to objects with template-matching features but are also important for the subsequent identification of selected objects, which is based on a match of their perceptual features and the properties of the current search templates. Even if color templates activated by word cues produce no benefits for attentional target selection, they may still facilitate the speed with which particular objects can be recognized as targets.

Overall, the current results suggest that color signals are much more effective in facilitating attentional guidance processes in visual search when target identity is specified by picture cues than when target objects are merely specified verbally. Although representations of known target colors that are activated once a target object has been visually presented are clearly important for the efficient control of attentional target selection, it is clear that other visual dimensions also contribute to the superiority of pictorial over verbal target specifications. In both experiments of this study, RTs were delayed and N2pc components emerged later and were attenuated in response to the first target in each trial run, and this was the case not only with colored search displays but also with displays that did not contain color information. This shows that, after the first visual encounter with a target object, search templates include much more precise visual target representations in dimensions other than color, resulting in a faster allocation of attention to target-matching objects and in additional benefits in the template-guided identification of these objects.

Previous research has demonstrated the importance of color information for object recognition (e.g., Gegenfurtner & Rieger, 2000) and for the control of attentional target selection in visual search (e.g., Wolfe & Horowitz, 2004). The current study has provided new insights into the role of color during the activation of new attentional templates for real-world target objects. Even when all visual properties of a target object are known in advance and the selection of these objects can be guided by search templates that represent all of these properties, the availability of color information still facilitates the speed of attentional target selection. Search templates that are activated in response to word cues usually also include representations

of expected target colors, unless participants know in advance that such representations will not be useful in guiding the subsequent allocation of attention to target objects.

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Note

1. Although it would in principle be possible to compute N2pc components in response to target objects with high color diagnosticity only, the low number of such objects included in this study is insufficient to compute meaningful N2pc components. In addition, these N2pcs would in any case reflect the joint contributions of color and shape representations in search templates that are set up in response to word cues, rather than the specific impact of diagnostic object colors on template-guided search.

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