Qualitative Differences in the Guidance of Attention During Single-Color and Multiple-Color Visual Search: Behavioral and Electrophysiological Evidence

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To find out whether attentional target selection can be effectively guided by top-down task sets for multiple colors, we measured behavioral and ERP markers of attentional target selection in an experiment where participants had to identify color-defined target digits that were accompanied by a single gray distractor object in the opposite visual field. In the One Color task, target color was constant. In the Two Color task, targets could have one of two equally likely colors. Color-guided target selection was less efficient during multiple-color relative to single-color search, and this was reflected by slower response times and delayed N2pc components. Nontarget-color items that were presented in half of all trials captured attention and gained access to working memory when participants searched for two colors, but were excluded from attentional processing in the One Color task. Results demonstrate qualitative differences in the guidance of attentional target selection between single-color and multiple-color visual search. They suggest that top-down attentional control can be applied much more effectively when it is based on a single feature-specific attentional template.

Keywords: selective attention, top-down control, task set, event-related brain potentials, vision

The attentional selection of visual target objects among distractors is guided by top-down task sets. Even highly salient visual events such as feature singletons usually attract attention only when they match current target-defining features, but not when they are task-irrelevant (Folk, Remington, & Johnston, 1992). The role of top-down attentional control settings (or attentional templates; Duncan & Humphreys, 1992) during attentional object selection has been demonstrated conclusively with behavioral and neuroscientific measures (e.g., Chelazzi, Duncan, Miller, & Desimone, 1998; Eimer & Kiss, 2008; Folk et al., 1992). Attentional templates also feature prominently in computational models of selective attention and visual search (e.g., Bundesen, 1990; Wolfe, 1994, 2007). Features such as color, size, orientation, or movement direction can be employed to guide attention toward the location of candidate target events. When one of these features is represented as task-relevant in an attentional template, feature-matching visual events trigger rapid attentional capture (e.g., Eimer, Kiss, Press, & Sauter, 2009; Girelli & Luck, 1997), while nonmatching objects are effectively excluded from attentional processing in attention and working memory (e.g., Eimer, Kiss, & Nicholas, 2011).

The top-down guidance of attention by templates that specify one particular visual feature as task-relevant is swift and efficient. However, target objects in the attention lab and in the real world are often defined by more than one single feature. When searching for a target that differs from distractors by a conjunction of features (e.g., a red horizontal bar among green horizontal and red vertical bars), both features need to be included in an attentional template. Current models of visual search (e.g., Wolfe, 2007) assume that target-defining features from different dimensions (e.g., color and orientation) are represented separately and, therefore, affect the allocation of attention in a parallel and independent fashion (see also Olivers, Meijer, & Theeuwes, 2006). But can attention be guided by more than one visual feature *from the same dimension*? At first glance, this should not be particularly difficult. Attentional templates are assumed to be representations in working memory (e.g., Olivers, Peters, Houtkamp, & Roelfsema, 2011), and visual working memory is known to have a storage capacity of 3–4 items (e.g., Cowan, 2001; Vogel & Machizawa, 2004). It should, therefore, be possible to simultaneously activate two or three attentional templates for different simultaneously task-relevant colors. If this was the case, attentional guidance by two different color templates might be just as efficient as guidance by a single color-specific template.

However, there is substantial evidence that attentional target selection is impaired when it has to be guided by multiple-color templates. Wolfe et al. (1990) demonstrated that visual search for targets that are defined by a conjunction of two colors is less efficient than search for color- and orientation-defined conjunction targets. To account for this finding, the Guided Search model (Wolfe, 1994, 2007) postulates that attentional templates specify exactly one feature for each dimension at any time. Along similar lines, Houtkamp and Roelfsema (2009) found that target detection

performance in a rapid serial visual presentation (RSVP) stream was worse when observers searched for one of two possible objects or features than when they searched for a single object/feature. Modeling of these results suggested that exactly one attentional template was active at a time (see also Olivers et al., 2011). The difficulty of simultaneously maintaining two attentional templates was demonstrated by Dombrowe, Donk, and Olivers (2011). These authors found that successive eye movements to two color-defined targets were less accurate and slower when targets differed in their color than when they had the same color, and interpreted this difference as costs associated with switching between attentional sets. Further evidence for single-template guidance was reported by Stroud et al. (2011), who used visual search tasks designed to resemble airport security checking procedures. Search for a single object or for two different objects that were defined by the same color was much more efficient than search for two different objects in different colors. In the latter case, response times (RTs) were slow and distractor objects with nontarget colors were fixated more often than in a single-color search control condition (see also Menneer, Cave, & Donnelly, 2009, for similar observations).

While these findings strongly suggest that attention cannot be simultaneously guided by more than one feature from the same dimension, results from other recent studies indicate that top-down attentional control may be more flexible. Irons, Folk, and Remington (2012) employed the spatial cueing paradigm introduced by Folk, Remington, and Johnston (1992). Spatially uninformative feature singleton cues preceded target arrays, and spatial cueing effects on target RTs were interpreted as reflecting task-set contingent involuntary attentional capture by these cues. Irons et al. (2012) asked participants to search for either of two color-defined targets among distractors. Each target array was preceded by a color singleton cue in one of the two target-defining colors or in a different nontarget color. As expected, target-color singleton cues triggered RT spatial cueing effects indicative of task-set contingent attentional capture. But critically, nontarget-color singleton cues did not produce any spatial cueing effects, suggesting this color was not part of the current task set. This was the case even when target-matching and target-nonmatching cue colors were not linearly separable in color space (e.g., Bauer, Jolicoeur, & Cowan, 1996). These results by Irons et al. (2012) suggest that participants were able to adopt a feature-specific task set for two different colors, that is, to simultaneously activate two different color-specific attentional templates. Further evidence for multiple color templates was reported by Moore and Weissman (2010). In their experiment, observers had to detect target letters defined by either of two possible colors in a central RSVP stream, and to ignore lateral distractors that appeared just before the target. Distractors captured attention (as reflected by performance impairments for subsequent targets) when they matched one of the two potential target colors, but not when their color was task-irrelevant. This pattern of effects again suggests that two color-specific attentional templates can be maintained simultaneously. A similar conclusion was drawn by Beck, Hollingworth, and Luck (2012) on the basis of eye tracking data obtained in two tasks where observers either searched sequentially for one color before switching to another color, or searched for both colors simultaneously. Finally, Adamo, Pun, Pratt, and Ferber (2008) reported evidence that observers can simultaneously maintain two task sets for specific target color/

location combinations (e.g., green on the left and blue on the right).

This brief review of recent behavioral studies of multiple-color search shows that the question whether attention can be guided by templates that specify two or more features from the same dimension remains open. The aim of the present study was to combine behavioral and electrophysiological measures to find out whether and how the efficiency of attentional target selection differs when it is guided by single-color versus multiple-color task sets. We chose to employ a pared-down version of visual search where each target stimulus was accompanied by a single distractor object in the contralateral visual field. On each trial, two different digits (1, 2, 3, or 4) were presented to the left and right of fixation. One of these digits was colored, the other was gray. Participants had to select a digit when it had a prespecified target color, and report its value by pressing one of four response keys. To increase the attentional demands of this digit identification task, all digits were flanked by two hash marks (see Figure 1). There were four different possible colors (red, green, yellow, and blue), and the critical manipulation was whether targets were defined by one specific color or could have one of two colors. In the One Color task, there was one unique target color that remained constant throughout this task. On half of all trials, a target-color item was presented together with a gray distractor. On the other half, an item in one of the three nontarget colors appeared together with a gray distractor, and no response was required. In the Two Color task, there were two possible target colors and two distractor colors. On each trial, a digit appeared unpredictably and randomly in one of these four colors and was accompanied by a gray distractor item. Thus, target-color and nontarget-color trials were equally likely, as in the One Color task. Importantly, target and nontarget colors in the Two Color task were not linearly separable in color space: Half of all participants searched for a red or green target, and had to ignore yellow or blue items on nontarget trials, and this target/nontarget color assignment was reversed for the other participants.

If attentional target selection was equally effective when it is guided by single-color or multiple-color attentional templates, RTs to target-color digits should be similar in the One and Two Color tasks. In contrast, if only a single color-specific attentional template can be activated at any time, there should be substantial RT costs in the Two Color task. To find out whether and how the difference between single and multiple-color search affects the time course of target selection, event-related brain potentials (ERPs) were recorded during task performance, and the N2pc component was measured as an online electrophysiological marker of spatially selective attentional processing. The N2pc is an enhanced negativity that emerges over lateral extrastriate visual cortex around 200 ms after the onset of visual arrays that contain a candidate target object. This component is triggered contralateral to the side of this object during the attentional selection of visual target items among distractors (Eimer, 1996; Eimer & Kiss, 2008; Grubert, Krummenacher, & Eimer, 2011; Luck & Hillyard, 1994; Mazza, Turatto, Umiltà, & Eimer, 2007; Woodman & Luck, 1999). The sensitivity of the N2pc to top-down control has been demonstrated in previous ERP studies of task-set contingent attentional capture: Feature singleton cues trigger an N2pc when they are task-set matching (e.g., red singleton cues during search for red targets) but not when they are task-irrelevant (e.g., red singleton cues during search for small targets; e.g., Eimer & Kiss, 2008;
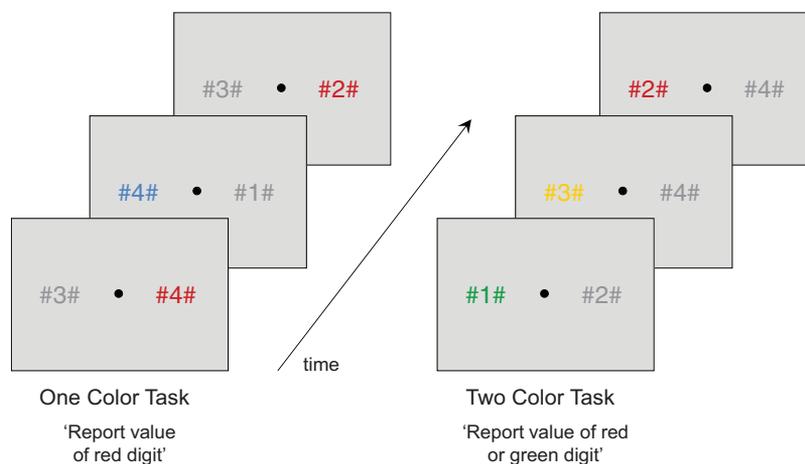
Figure 1. Illustration of search displays used in the One Color task (left) and Two Color task (right). The display background was originally black. On each trial, one colored item was always presented together with a gray distractor item on the opposite side of the display.

Eimer et al., 2009; Leblanc, Prime, & Jolicoeur, 2008; Lien, Ruthruff, Goodin, & Remington, 2008).

In previous spatial cueing experiments, the N2pc component was used to demonstrate that attentional capture is contingent on top-down task sets. In the present study, we employed the N2pc as a temporal marker for the efficiency of attentional target selection during single-color and multiple-color search. The critical question was whether the N2pc to color-defined targets would emerge earlier in the One Color task. If top-down attentional templates can be set to include more than one target color, as suggested by recent behavioral results (e.g., Irons, Folk, & Remington, 2012; Moore & Weissman, 2010), attentional target selection might be equally fast in both tasks, and there should be no systematic N2pc onset latency differences between them. In contrast, if observers can only maintain one color-specific attentional template at a time (e.g., Houtkamp & Roelfsema, 2009; Olivers et al., 2011), this should affect the speed of attentional target selection in the Two Color task relative to the One Color task, and result in a delayed onset of the N2pc in the Two Color task.

If only one color-specific attentional template can be active at any given moment, the question arises which (if any) of the two possible templates is active on individual trials in the Two Color task. It is conceivable that color-based target selection commences without template guidance in an online fashion after the presentation of each target/distractor stimulus pair. In this case, a strongly delayed and attenuated N2pc component should be triggered in the Two Color task (see Eimer et al., 2011, for the N2pc signature of attentional target selection in the absence of advance preparation). Another possibility is that target selection is guided by color-specific attentional templates in the Two Color task, and that their content is determined by the immediately preceding trial. Once a target has been selected on the basis of its color, the corresponding color-specific attentional template may be maintained and affect target selection on the next trial (see Maljkovic & Nakayama, 1994, for automatic intertrial priming effects in popout visual search, and Eimer, Kiss, & Cheung, 2010, for ERP correlates of this "priming of popout" effect). To investigate this possibility, we

analyzed N2pc components in the Two Color task separately for target-color repetition and target-color change trials. If the identity of a single color-specific attentional template was determined by the color of the previous target, N2pc latencies on target-color repetition trials should be similar in the One Color and Two Color tasks, but should be substantially delayed on target-color change trials in the Two Color task. If it was possible to simultaneously maintain two color-specific attentional templates (as suggested by Irons et al., 2012), the identity of the preceding target should have little impact on target N2pcs in the Two Color task.

Another potential important difference between multiple-color and single-color search concerns the ability to ignore nontarget objects. While attentional guidance by single-feature templates is likely to result in the effective exclusion of nontarget items from attentional processing in perception and working memory (e.g., Eimer et al., 2011), the capacity to exclude nontargets might be impaired during multiple-feature search. The inclusion of trials with nontarget-color digits allowed us to directly assess the exclusion of task-irrelevant colored objects from attentional processing in perception and working memory during single-color and multiple-color search. If this ability was impaired in the Two Color task, nontarget-color digits should elicit an N2pc in this task, but not in the One Color task. To assess the access of target-color and nontarget-color items to working memory, we also measured the sustained posterior contralateral negativity (SPCN) in both tasks. This component, which is also known as contralateral delay activity (CDA), typically emerges around 350 ms after stimulus onset at lateral posterior electrodes, and is associated with the spatially selective activation of target representations in working memory (Mazza et al., 2007; Vogel & Machizawa, 2004). In the One Color task, the guidance of attentional selectivity by a color-specific attentional template should result in the successful exclusion of nontarget-color stimuli from spatially selective perceptual and mnemonic processing, and thus, in the absence of any N2pc and SPCN components to these stimuli. The critical question was whether this would also be the case in the Two Color task. If attentional selectivity is impaired during multiple-color search

nontarget-color items should sometimes gain access to visual memory, and this should be reflected by reliable SPCN components. In contrast, if multiple attentional templates can be maintained simultaneously, the exclusion of nontarget-color items from working memory should be similarly effective in both tasks.

Method

Participants

Fourteen observers were paid to participate in this experiment. One was excluded due to exceedingly high error rates (> 30%), and another because of a large number of horizontal eye movements. The remaining 12 participants (nine female, aged 19 – 42 years; mean age 29 years) were all right-handed and had normal or corrected-to-normal vision.

Stimuli and Procedure

Stimuli were presented on a 22" Samsung wide SyncMaster 2233 LCD monitor (100 Hz refresh rate; 16 ms black-to-white-to-black response time, as verified with a photodiode), against a black background. On each trial, a pair of stimuli was presented for 150 ms to the left and right of fixation at a horizontal eccentricity of 2.6° relative to central fixation. Both lateral stimuli contained a central digit that was flanked by on both sides by hash marks, and subtended a visual angle of 2.2° × 0.7°. Each stimulus array contained one colored item on one side and an equiluminant gray item (CIE color coordinates .324/.348) on the other side (see Figure 1). The colored item was either red (CIE color coordinates .609/.338), yellow (.438/.452), green (.262/.558), or blue (.205/.191). The two digits shown on each trial were chosen randomly, with the constraint that they were never identical. The position of the colored item (left or right) varied randomly across trials. All digit stimuli were equiluminant (12 cd/m^2).

On half of all trials, the colored stimulus matched a current target color, and participants had to identify and respond to the central digit. The other half of all trials contained a nontarget-color item and a gray item, and no response was required. The experiment included two blocked task conditions. In the One Color task, participants were instructed to always select the item in one predefined target color, in order to identify the central digit and to press the corresponding response button. Target color was varied across participants, with each of the four colors serving as target color for three participants. Each block contained 15 target-color trials and 15 nontarget-color trials (five trials for each of the three nontarget colors), with the colored item presented on the left or right, respectively, resulting in 60 trials per block. In the Two Color task, participants had to select the object in one of two possible target colors in order to identify and respond to the central digit. For half of all participants, target colors were red or green, while nontarget colors were yellow or blue, and this assignment was reversed for the other six participants. This procedure ensured that the two target colors were not linearly separable in color space from the two distractor colors. Target colors were swapped across the two tasks: Participants who searched for red or green targets in the One Color task searched for blue and yellow targets in the Two Color task, and vice versa. Each block contained 40 target-color and 40 nontarget-color trials (10 trials for each of the four colors)

with a colored item on the left or right, respectively, resulting in 80 trials per block. There were six successive blocks for the One Color task, and nine successive blocks for the Two Color task. In order to neutralize any color-specific carry-over effects across the two tasks, task order was counterbalanced across participants.

The intertrial interval between the offset of one stimulus array and the onset of the array on the next trial was 1,650 ms in both tasks. Participants were instructed to maintain central fixation, to identify target-color digits when they were present, and to press one of four horizontally arranged response keys with the middle or index finger of their left or right hand. The digit-to-key assignment was spatially compatible (i.e., "1" was mapped to the leftmost and "4" to the rightmost key). One practice block preceded the experimental blocks in both tasks.

EEG Recording and Data Analyses

EEG was DC-recorded from 23 scalp electrodes mounted in an elastic cap at standard positions of the extended 10/20 system at sites Fpz, Fz, F3, F4, F7, F8, FC5, FC6, Cz, C3, C4, T7, T8, CP5, CP6, Pz, P3, P4, P7, P8, PO7, PO8, and Oz. The continuous EEG was sampled at a rate of 500 Hz, with a digital low-pass filter of 40 Hz. All electrodes were online referenced to the left earlobe and rereferenced offline to the average of both earlobes. No further filters were applied after EEG acquisition. Trials were segmented from 100 ms before to 700 ms after stimulus onset. Trials with artifacts (HEOG exceeding ± 30 μV; Fpz ± 60 μV; all other electrodes ± 80 μV), or with incorrect or missing responses to target digits were excluded from all further analyses.

EEG was averaged for all combinations of task (One Color, Two Color), side of colored object (left or right visual field) and object color (target or nontarget color). In the One Color task, separate averages were computed for target-color repetition trials where target color was the same than on the immediately preceding trial and for target-color trials that were preceded by a nontarget-color trial. In the Two Color task, separate averages were computed for target-color repetition trials, for target-color change trials (i.e., target-color trials preceded by a trial with the other target color), and for target-color trials preceded by a nontarget-color trial. N2pc components to target-color arrays were quantified on the basis of mean amplitudes obtained in a 180–280 ms time window after stimulus onset at lateral posterior electrodes PO7 and PO8. N2pc onset latencies were determined with a jackknife-based procedure from difference waveforms obtained by subtracting ERPs at PO7/8 ipsilateral to the side of the target from contralateral ERPs. This procedure estimates onset latencies from grand averages that are computed for subsamples of participants where one participant is successively excluded from the original sample (Miller, Patterson, & Ulrich, 1998). N2pc onset was defined as the absolute time-point when the voltage on the ascending flank of the N2pc difference wave exceeded an absolute threshold value of −1 μV. N2pc onset differences between the One Color and Two Color task and effects of trial history on N2pc latencies were analyzed with paired t-tests, and t-values were corrected (denoted as t_c) according to the formula described by Ulrich and Miller (2001) and Miller et al. (1998). The SPCN component was quantified on the basis of ERP mean amplitudes measured during the 350–700 ms poststimulus time window at electrodes PO7/8.

Results

Behavioral Performance

Trials with anticipatory RTs (faster than 200 ms) and very slow responses (RTs longer than 1,200 ms) were excluded from analysis (less than 0.5% of all trials). Target RTs in the One Color task were significantly faster than in the Two Color task (683 ms vs. 711 ms; $t(11) = 3.0$; $p = .013$). RTs on target-color change trials in the Two Color task were delayed relative to target-color repetition trials, 717 ms vs. 683 ms; $t(11) = 5.0$, $p = .001$. Target-color repetition trials were faster in the One Color task than in the Two Color task (670 ms vs. 683 ms), but this difference was not significant, $t(11) = 1.1$, $p = .286$. As would be expected, target RTs were generally delayed on trials that were preceded by a Nogo trial with a task-irrelevant nontarget color item relative to target-color repetition trials, both in the One Color task, 670 ms vs. 694 ms; $t(11) = 3.2$, $p = .009$, and in the Two Color task, 683 ms vs. 721 ms; $t(11) = 6.5$, $p < .001$.

Incorrect responses to targets were recorded on 2.9% and 2.2% of all trials in the Two Color and One Color tasks, respectively, and this difference was not reliable. There were no significant differences between the One Color and Two Color tasks for the percentage of missed targets (0.8% vs. 1.4%) and for False Alarms to nontarget-color items (below 0.2% in either task).

ERP Results

Figure 2 (top and middle panel) shows ERPs obtained in the One Color task and in the Two Color task at electrodes PO7/8 contralateral and ipsilateral to the side of a colored item, separately for trials where this item matched a current target color (left side) and for trials where its color was task-irrelevant (right side). Target-color items triggered N2pc components in both tasks, but the N2pc appeared to emerge earlier in the One Color task. This is shown more clearly in the difference waveforms obtained by subtracting ipsilateral from contralateral ERPs (Figure 2, bottom panel, black lines). On trials with nontarget-color items, no N2pc was visible in the One Color task, whereas an attenuated N2pc appeared to be present in the Two Color task, indicative of differences in the ability of nontarget-color objects to capture attention between the two tasks.

Latency analyses confirmed that the N2pc to target-color objects emerged faster in the One Color task than in the Two Color task, 178 ms vs. 214 ms; $t_c(11) = 5.6$, $p = .001$. A main effect of contralaterality, $F(1, 11) = 51.7$, $p < .001$ on N2pc mean amplitudes measured in the 180–280 ms poststimulus interval for target-color trials demonstrated that the N2pc was reliably present. There was no significant interaction between contralaterality and task, $F(1, 11) = 1.6$, $p = .231$. When only the early part of the N2pc was analyzed in a 180–230 ms poststimulus time window, this interaction was significant, $F(1, 11) = 5.4$, $p = .040$. N2pc amplitudes were larger in the One Color task during this interval, which primarily reflects the onset latency difference between the two tasks.

For nontarget-color objects, there was a reliable interaction between contralaterality and task, $F(1, 11) = 7.6$, $p = .019$ for N2pc mean amplitudes, suggesting that an N2pc was present in the Two Color task and absent in the One Color task. This was confirmed by subsequent t-tests, which showed a reliably enhanced contralateral negativity in response to nontarget-color objects in the Two Color task, $t(11) = 2.4$, $p = .036$, but not in the One Color task ($t < 1$). The onset of the N2pc to nontarget-color items in the Two Color task was reliably delayed relative to the N2pc to target-color items, 214 ms vs. 240 ms; $t_c(11) = 2.9$, $p = .047$.

As can be seen in Figure 2, the N2pc was followed by the SPCN component on trials with target-color items in both tasks. On nontarget-color trials, the SPCN was attenuated (Two Color task) or entirely absent (One Color task). This was statistically confirmed by analyses of ERP mean amplitudes at PO7/8 in the 350–700 ms poststimulus interval. In both tasks, main effects of contralaterality, both $F(1, 11) > 38.2$, both $p < .001$, reflected the presence of an SPCN. These were accompanied by highly significant interactions between contralaterality and color—target color vs. nontarget color; both $F(1, 11) > 39.4$, both $p < .001$—confirming the reduction of this component on nontarget-color trials in both tasks. To test whether nontarget-color objects elicited SPCN components only in the Two Color task, an additional analysis compared the SPCN for nontarget-color ERPs across both tasks. There was an interaction between contralaterality and task, $F(1, 11) = 6.7$, $p = .025$. Follow-up t-tests confirmed the absence of an SPCN for nontarget-color items in the One Color task, $t(11) < 1$, and revealed the presence of a small but reliable SPCN to these items in the Two Color task, $t(11) = 3.4$, $p = .006$.

Figure 3 shows the impact of trial history on contralateral and ipsilateral ERPs in response to target-color items stimuli in the One Color and Two Color tasks. Results are shown separately for target-color repetition trials, target-color change trials (which were only present in the Two Color task), and for target-color trials that were preceded by a trial with a nontarget-color stimulus. The contralateral/ipsilateral difference waveforms in Figure 3 (bottom left panel) illustrate the effects of trial history on N2pc onset latencies. In the Two Color task, the N2pc emerged reliably earlier on target-color repetition trials (203 ms) than on target-color change trials, 236 ms; $t_c(11) = 4.5$, $p = .002$. In the One Color task, target-color repetition trials triggered an N2pc with an onset latency of 177 ms, which was reliably earlier than the N2pc to target-color repetition trials in the Two Color task, $t_c(11) = 3.1$, $p = .010$. There were no reliable N2pc onset latency differences between target-color repetition trials and target-color trials preceded by nontarget-color trials in either task, both $t_c(11) < 2.2$, both $p > .139$; see Figure 3, bottom right panel.

Discussion

The aim of this study was to find out whether attentional target selection can be effectively guided by top-down task sets for more than one task-relevant color (i.e., multiple color-specific attentional templates), as suggested by recent behavioral findings (Irons et al., 2012; Moore & Weissman, 2010). The alternative hypothesis was that attentional control settings specify exactly one feature for each dimension (Wolfe, 2007), which implies that only a single feature-specific template can be active at any time (Houtkamp & Roelfsema, 2009; Olivers et al., 2011). We employed an attentional selection task that was pared down to its essential elements: Participants had to identify color-defined target digits that were
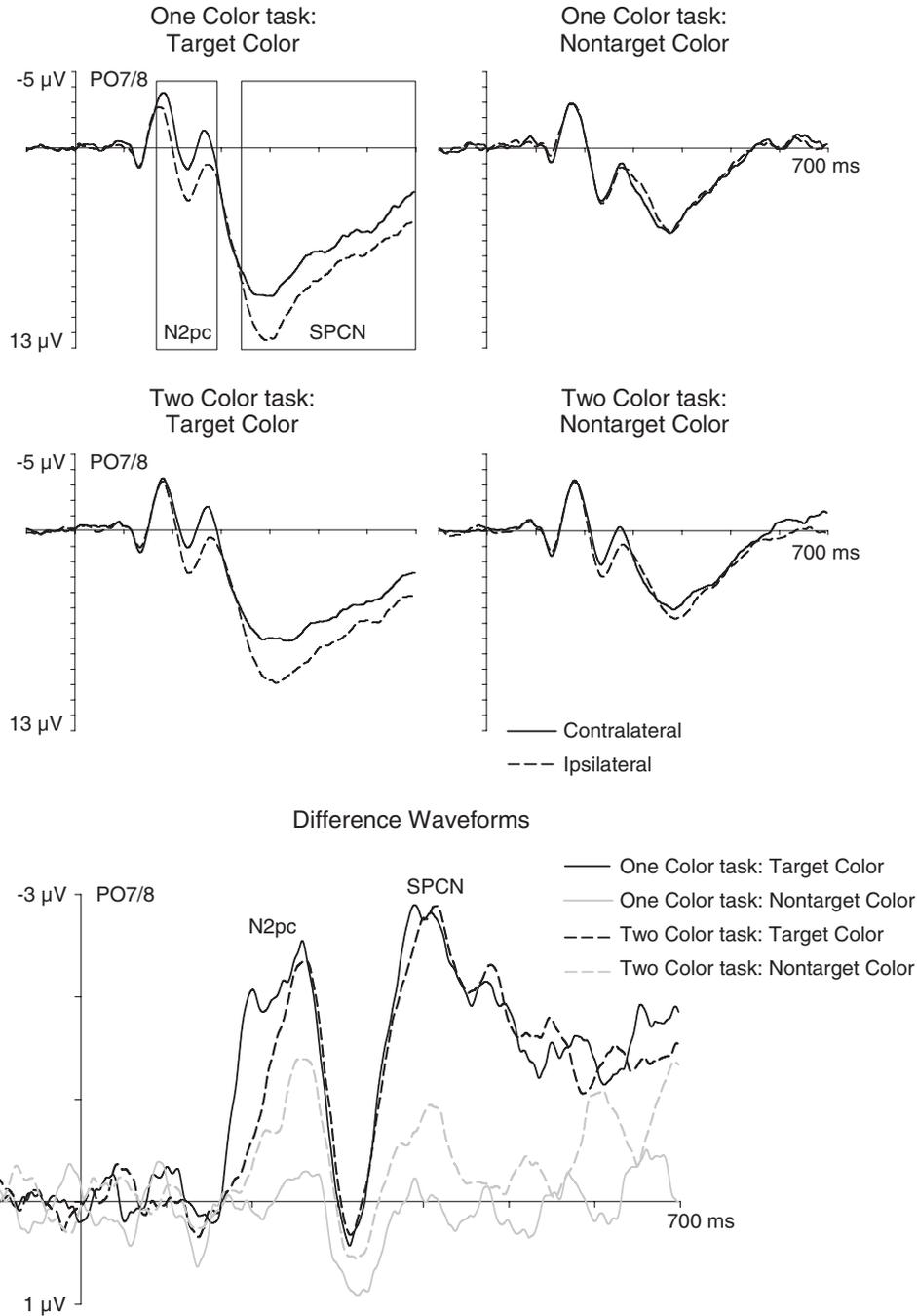
Figure 2. Grand-average ERPs measured at posterior electrodes PO7/8 contralateral and ipsilateral to the location of target-color items (left) and nontarget-color items (right) in the One Color task (top panel) and Two Color task (middle panel). The bottom panel shows difference waveforms obtained by subtracting ipsilateral from contralateral ERPs in response to target-color and nontarget-color items in the One Color and Two Color tasks.

accompanied by a single gray distractor object in the opposite visual field. One advantage of this minimalist visual search procedure is that it required only a single target/nontarget discrimination on each trial, rather than sequential shifts of attention between multiple candidate target objects, as in standard visual

search tasks. Another advantage of using bilateral equiluminant stimulus pairs was that there were no feature singletons that might attract attention in a salience-driven bottom-up fashion, thereby ensuring that target selection was exclusively determined by top-down attentional templates.

Our results demonstrated that attentional target selection is guided much more effectively during single-color search as compared to multiple-color search. Efficient color-based target selection was observed in the One Color task, reflected by fast RTs and short-latency N2pc components. In the Two Color task, RTs were slower, and the N2pc to color targets emerged later than in the One Color task. The observation that the RT difference between the two tasks (28 ms) was similar to the estimated N2pc onset latency difference on target-color trials (36 ms) suggests that the behavioral performance costs in the Two Color task were primarily due to a delay in the initial attentional selection of color targets at early visual-perceptual processing stages. These findings demonstrate that attentional control settings for a single color and for multiple colors are not equivalent in terms of their efficiency: The attentional selection of color targets in extrastriate visual areas is initiated more rapidly when attention is guided by a unique color template.[1]

Additional evidence for qualitative differences between single-color and multiple-color selection tasks was provided by the ERP results obtained on nontarget-color trials (Figure 2, right panel). These data showed that the ability to exclude task-irrelevant nontarget-color items from spatially selective attentional processing in visual perception and working memory was impaired during multiple-color visual search. In the One Color task where target selection was guided by a color-specific attentional template, nontarget-color objects did not trigger N2pc or SPCN components, indicating that they were unable to attract attention. In marked contrast, reliable N2pc and SPCN components were elicited by nontarget-color items in the Two Color task, reflecting less-than-perfect attentional selectivity. It should be noted that these components were much smaller and emerged later than those triggered by target-color objects (see Figure 2, bottom panel), which shows that visual processing was not completely color-unselective in this task.[2] In principle, participants could have adopted a generic feature-unspecific task set for color ("any color, regardless of its value") in the Two Color task, which would have been reflected in equivalent N2pc amplitudes and latencies for target-color and nontarget-color objects. The presence of marked N2pc differences rules out this possibility. Nevertheless, the presence of reliable N2pc and SPCN components to nontarget-color items in the Two Color task provides clear evidence that these items captured attention and gained access to working memory on at least some trials, thus demonstrating that the efficiency of feature-based selection (i.e., the ability to attend to specific values within the task-relevant color dimension) was reduced in this task.[3] These observations are consistent with previous results by Stroud et al. (2011), who found that nontarget-color objects are fixated frequently during search for two different target colors. The reduction in the efficiency of color-specific selectivity in the Two Color task further underlines the special status of attentional guidance by a unique feature attribute.

If two color-specific attentional templates cannot be effectively maintained simultaneously, the question arises whether any color templates were active at all in the Two Color task and if so, how they were chosen. The trial history effects observed in this task suggest an answer. RTs were faster and the N2pc emerged earlier on target-color repetition trials as compared to target-color change trials, indicating that target selection was guided by a color-specific template that matched the color of the immediately pre-

ceding target. If participants had been able to simultaneously maintain two color templates, the identity of the previous target should have had little if any effect on the speed and efficiency of attentional target selection. One could argue that these intertrial effects have little to do with top-down attentional templates, but instead reflect automatic bottom-up color priming triggered by the target on the preceding trial (e.g., Maljkovic & Nakayama, 1994). If this was the case, the N2pc should emerge earlier on target-color repetition trials relative to target-color trials that were preceded by a nontarget trial. The fact that this was not the case in either task (Figure 3, bottom right panel) is inconsistent with this hypothesis. This observation that the N2pc did not emerge earlier on target-color repetition trials than on target trials that were preceded by a nontarget trial also suggests that the maintenance of the template that was involved in selecting the previous target in the Two Color task primarily resulted in costs on target-color change trials, but produced little benefit for attentional target selection on target-color repetition trials.

If attentional templates during multiple-color search are determined by the identity of the previous target, one might expect target selection efficiency on target-color repetition trials in the Two Color task to be equivalent to single-color search. The observation that the N2pc emerged earlier on target-color repetition trials in the One Color task than in the Two Color task (Figure 3, bottom left panel) suggests that residual multiple-color task set costs on attentional target selection remain even when the current target color matches that of the previously selected target. Such costs might be due to competitive interactions between the current attentional template and a representation of the other target-defining color that is held as an accessory working memory item (e.g., Olivers et al., 2011). The generally reduced color selectivity in the Two Color task that was revealed by the presence of N2pc

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[1] Performance was worse in the Two Color task relative to the One Color task in spite of the fact that the Two Color task included twice as many trials (720 versus 360 trials), which could have produced stronger training effects. To assess the role of training, we conducted an additional RT analysis that included all trials of the One Color task but only the first 360 trials of the Two Color task. Results were virtually identical to the results obtained when all trials were included, thus demonstrating that differential learning effects did not contribute to the observed behavioral differences between the two tasks.

[2] In an analysis of N2pc mean amplitudes obtained in the Two Color task with item color (target color versus nontarget color) as additional factor, a highly significant interaction was obtained between contralaterality and target color, $F(1, 11) = 15.4$, $p < .005$, thereby formally confirming the reduction of the N2pc for nontarget-color as compared to target-color items.

[3] Figure 2 suggests that nontarget-color items triggered an enhanced contralateral positivity at around 350 ms post-stimulus, in particular in the One Color task. Similar "Pd" components that were observed in previous ERP studies of visual attention (Hickey, Di Lollo, & McDonald, 2009; Kiss, Grubert, Petersen, & Eimer, 2012; Sawaki & Luck, 2010) have been linked to the spatially selective inhibition of salient distractor items. Analyses of ERP mean amplitudes to nontarget-color items at PO7/8 between 300 ms and 350 ms post-stimulus confirmed the presence of a reliably enhanced contralateral positivity in the One Color task, $t(11) = 3.4$, $p < .01$, while there was no significant difference in the Two Color task. This pattern suggests that the capacity to inhibit task-irrelevant color items was stronger in the One Color task where attentional selectivity was controlled by a color-specific attentional template. However, because the relevant interaction between contralaterality and task was not reliable, this conclusion must remain speculative at present.
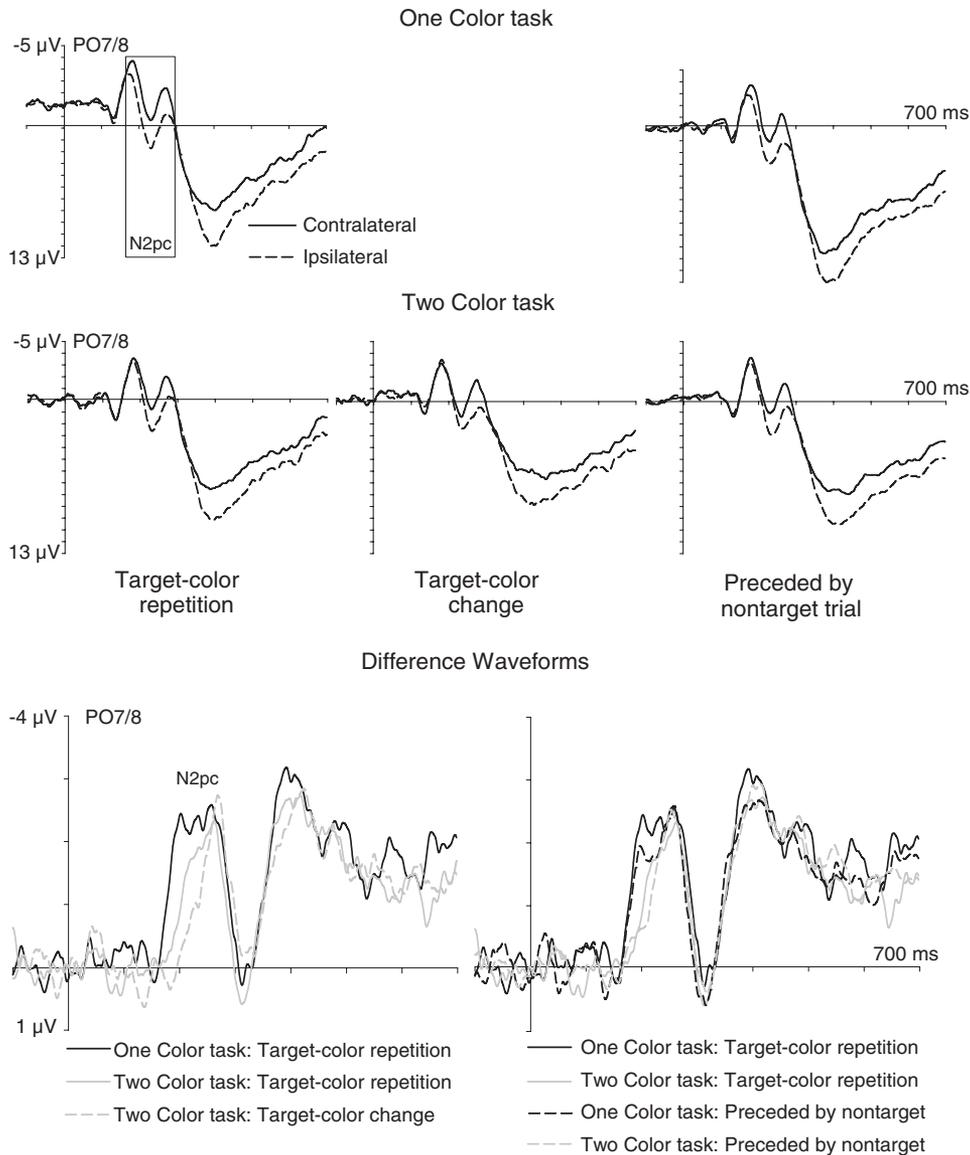
One Color task

-5 µV PO7/8

13 µV

N2pc

—— Contralateral
- - - Ipsilateral

700 ms

Two Color task

-5 µV PO7/8

13 µV

Target-color
repetition

Target-color
change

Preceded by
nontarget trial

700 ms

Difference Waveforms

-4 µV PO7/8

N2pc

1 µV

700 ms

—— One Color task: Target-color repetition
—— Two Color task: Target-color repetition
- - - Two Color task: Target-color change

—— One Color task: Target-color repetition
—— Two Color task: Target-color repetition
- - - One Color task: Preceded by nontarget
- - - Two Color task: Preceded by nontarget

Figure 3. Grand-average ERPs measured at posterior electrodes PO7/8 contralateral and ipsilateral to the location of target-color items in the One Color task (top panel) and Two Color task (middle panel). ERPs are shown separately for target-color repetition trials, target-color change trials and for target-color trials that were preceded by a trial with a nontarget-color item. The bottom panels show difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, for target-color repetition and target-color change trials (left), and for target-color repetition trials and trials where targets were preceded by a nontarget-color item (right).

and SPCN components to nontarget-color items in this task may also be the result of such competitive processes in working memory.

How can the conclusion that attentional control by a single color-specific attentional template is much more efficient than guidance by multiple templates be reconciled with results from previous behavioral experiments which suggest that top-down attentional control can be guided by more than one color simultaneously? It is important to note that the reduced target selection efficiency observed in the Two Color task does not imply that attentional guidance by multiple target colors is entirely impossi-

ble. As discussed earlier, the fact that N2pc and SPCN components were much smaller for nontarget-color objects than for target-color objects in the Two Color task demonstrates that some color-specific attentional control was available in this task. Nevertheless, our observation that this control was insufficient to completely prevent attentional capture by nontarget-color items seems inconsistent with previous behavioral studies which suggest that these items do not attract attention during multicolor search. Moore and Weissman (2010) found that lateral distractors captured attention when they matched one of the target colors, but not when their color was task-irrelevant. Along similar lines, Irons et al. (2012)

found spatial cueing effects indicative of attentional capture for target-color matching cues, but not for nonmatching cues. An important feature of both these studies was that the stimuli which triggered attentional capture were presented prior to the task-relevant stimuli for which behavioral performance was measured. This temporal delay may have been a critical factor for the emergence of color-selective capture effects in these experiments. In the present experiment, the N2pc to nontarget-color items was much smaller than the N2pc to target-color items in the Two Color task, indicating that their ability to attract attention was strongly reduced. In the studies by Moore and Weissman (2010) and Irons et al. (2012), the spatial bias triggered by nontarget-color distractors or cues may simply have been insufficient to produce reliable capture effects on responses to targets that were presented after a delay, while the bias elicited by target-color items may have been strong enough to produce measurable behavioral effects.

Alternatively and perhaps more interestingly, there may be systematic differences in the time course of attentional capture effects triggered by target-color matching and nonmatching stimuli during multiple-color search. Indirect evidence in support of this hypothesis comes from a recent study from our lab (Kiss, Grubert, & Eimer, 2012) where participants searched for targets defined by a specific color/size conjunction, and search arrays were preceded by spatially uninformative singleton cues that could match both, only one, or neither of the two target features. Partially matching cues (e.g., small red cues presented during search for large red targets) triggered N2pc components indicative of attentional capture, but failed to elicit corresponding spatial cueing effects for RTs to subsequent targets. We interpreted this apparent dissociation between electrophysiological and behavioral markers of attentional capture as evidence for a two-stage process: Partially matching cues triggered rapid attentional capture as demonstrated by the presence of an N2pc, but attention was then rapidly disengaged from these cues, resulting in the absence of behavioral spatial cueing effects (see also Adamo, Pun, & Ferber, 2010, for another example of a dissociation between electrophysiological and behavioral correlates of attentional capture). An analogous explanation could also account for the absence of behavioral attentional capture effects by nonmatching color distractors/cues during multiple-color search reported by Moore and Weissman (2010) and Irons et al. (2012): These stimuli may have initially attracted attention, but rapid attentional disengagement might have eliminated any effects on performance in response to subsequently presented targets. A straightforward prediction of this hypothesis is that task-set nonmatching color cues such as those employed by Irons et al. (2012) will trigger N2pc components indicative of attentional capture during multiple-color search, but no behavioral spatial cueing effects. This will need to be investigated in future studies.

The importance of investigating the time course of attentional object selection in multiple-color search was recently demonstrated by Dombrowe et al. (2011, Exp.2): When participants had to execute two successive eye movements to two targets in different colors, second saccades that were executed rapidly tended to be directed toward a distractor that matched the color of the first target, while longer-latency saccades were correctly directed toward the new color target. Dombrowe et al. (2011) suggested that it takes about 250 ms to switch between color-specific attentional sets. Such findings underline the importance of combining behav-

ioral markers of attentional capture with online electrophysiological or oculomotor measures in order to fully assess the properties of top-down attentional templates and how they affect visual processing in real time.

In summary, the current results provide new electrophysiological evidence that the guidance of attention is most effective when it is based on a single feature from a given dimension, and that there are qualitative differences between single-color and multiple-color visual search. This is in line with computational models of visual search (e.g., Wolfe, 1994, 2007) which postulate that top-down attentional weights are set for exactly one feature in each dimension. The reasons why visual search for two different target colors is so much less efficient than search for a single color-defined target remain somewhat mysterious, as working memory has sufficient capacity for two or three simultaneously active color templates (see Olivers, 2011; Olivers & Eimer, 2011, for further discussion). Although the quality of color-selective attentional processing is reduced during multiple-color search, it is not completely abolished, which implies that some top-down guidance can still be applied. The nature of this guidance will be an important focus for future research.

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