

# The Control of Single-color and Multiple-color Visual Search by Attentional Templates in Working Memory and in Long-term Memory

Anna Grubert<sup>1</sup>, Nancy B. Carlisle<sup>2</sup>, and Martin Eimer<sup>1</sup>

## Abstract

■ The question whether target selection in visual search can be effectively controlled by simultaneous attentional templates for multiple features is still under dispute. We investigated whether multiple-color attentional guidance is possible when target colors remain constant and can thus be represented in long-term memory but not when they change frequently and have to be held in working memory. Participants searched for one, two, or three possible target colors that were specified by cue displays at the start of each trial. In constant-color blocks, the same colors remained task-relevant throughout. In variable-color blocks, target colors changed between trials. The contralateral delay activity (CDA) to cue displays increased in amplitude as a function of color memory load in variable-color blocks, which indicates that cued target colors were held in working

memory. In constant-color blocks, the CDA was much smaller, suggesting that color representations were primarily stored in long-term memory. N2pc components to targets were measured as a marker of attentional target selection. Target N2pc were attenuated and delayed during multiple-color search, demonstrating less efficient attentional deployment to color-defined target objects relative to single-color search. Importantly, these costs were the same in constant-color and variable-color blocks. These results demonstrate that attentional guidance by multiple-feature as compared with single-feature templates is less efficient both when target features remain constant and can be represented in long-term memory and when they change across trials and therefore have to be maintained in working memory. ■

## INTRODUCTION

During visual search, observers have to find a particular target object that appears among multiple task-irrelevant distractors at an unpredictable location in the visual field. When some or all of the visual properties of the looked-for target are known in advance, the search process can be guided by this knowledge, so that attention can be deployed preferentially and more rapidly to objects that match one or more of the target-defining features (e.g., Wolfe, 2007). Such guiding representations of target features or objects are assumed to be held in visual working memory and have been described as attentional templates (e.g., Duncan & Humphreys, 1992) or top-down control settings (e.g., Folk, Remington, & Johnston, 1992). Search templates can be activated before the start of a particular search episode and facilitate target selection by guiding attention to the locations of objects with template-matching features (see Eimer, 2014, 2015, for a more detailed discussion of the cognitive and neural basis of template-controlled visual search).

Because visual working memory can typically hold three or four objects simultaneously (e.g., Cowan, 2001; Vogel, Woodman, & Luck, 2001), it would seem reasonable to

assume that multiple attentional templates may be concurrently active during visual search. If several search templates can operate in parallel, template-guided search for different possible target objects or features should be similarly effective as search for one specific object/feature. However, there is substantial evidence that this is not the case. For example, Houtkamp and Roelfsema (2009) demonstrated that target detection in rapid serial visual presentation tasks is impaired when observers search for two possible objects relative to single-object search. According to these authors, these impairments reflect the fact that only one attentional template for a particular target object can be active at any moment in time. Analogous capacity limitations of template-guided attention have been observed during visual search for simple visual features, such as color. Targets that are defined by one specific color are usually found rapidly, whereas the detection of color conjunction targets (e.g., red/blue targets among blue/green and red/green distractors) is inefficient (Wolfe et al., 1990). Again, this suggests that search can be guided by only one attentional template for one specific target color at a time (e.g., Wolfe, 2007). Along similar lines, Dombrowe, Donk, and Olivers (2011) found that sequential eye movements to two color-defined targets are slower and more error-prone when these targets differ in their color than when their color is identical, thereby

<sup>1</sup>University of London, <sup>2</sup>Lehigh University, Bethlehem, PA

demonstrating the difficulty of maintaining two color-specific attentional sets. Analogous evidence for impaired search performance during multiple-color search has also been obtained in experiments with naturalistic target objects that simulated real-world search tasks such as airport security screening (Stroud, Menneer, Cave, Donnelly, & Rayner, 2011; Menneer, Cave, & Donnelly, 2009). On the basis of such observations, Olivers, Peters, Houtkamp, and Roelfsema (2011) have argued that only a single working memory representation can be prioritized to serve as an attentional template at any given time. Other representations may be held simultaneously in working memory, but such “accessory” items are in a less active state and are therefore not able to affect the allocation of attention during visual search.

However, the results of other studies cast doubt on the hypothesis that attentional templates cannot represent more than one feature simultaneously. Moore and Weissman (2010) found that, when observers searched for one of two possible target colors in a central rapid serial visual presentation stream, lateral distractors that matched either of the two target colors impaired performance, whereas nonmatching color distractors did not. This suggests that the two color-matching distractors captured attention in a task set-dependent fashion and that more than one color-specific search template can be active at the same time. Further evidence for this conclusion was provided by Irons, Folk, and Remington (2012), who employed a spatial cueing paradigm where spatially uninformative color cues preceded search displays where targets could have one of two possible colors. On trials where the color cues matched either of the two target colors, spatial cueing effects indicative of task set contingent attentional capture were observed, with faster RTs to targets at cued as compared with uncued locations. Critically, no such attentional capture effects were triggered by cues that matched the color of a task-irrelevant distractor, which suggests that the distractor color was successfully excluded from the currently active task set. Irons et al. (2012) interpreted these results as evidence that observers can adopt a simultaneous task set for two different colors. Similar conclusions have been drawn by Beck, Hollingworth, and Luck (2012), who compared eye-tracking performance during single-color versus multiple-color search, and by Barrett and Zobay (2014), who measured and modeled set size functions in single- versus dual-target search.

Further support for the hypothesis that multiple color-specific attentional templates can be simultaneously active comes from recent ERP studies that measured the N2pc component as electrophysiological marker of attentional object selection. The N2pc is an enhanced negativity that is triggered at posterior scalp electrodes contralateral to targets that are presented among distractor objects in visual search arrays. This component typically emerges between 180 and 200 msec after stimulus onset of visual arrays that contain a candidate target object and is assumed

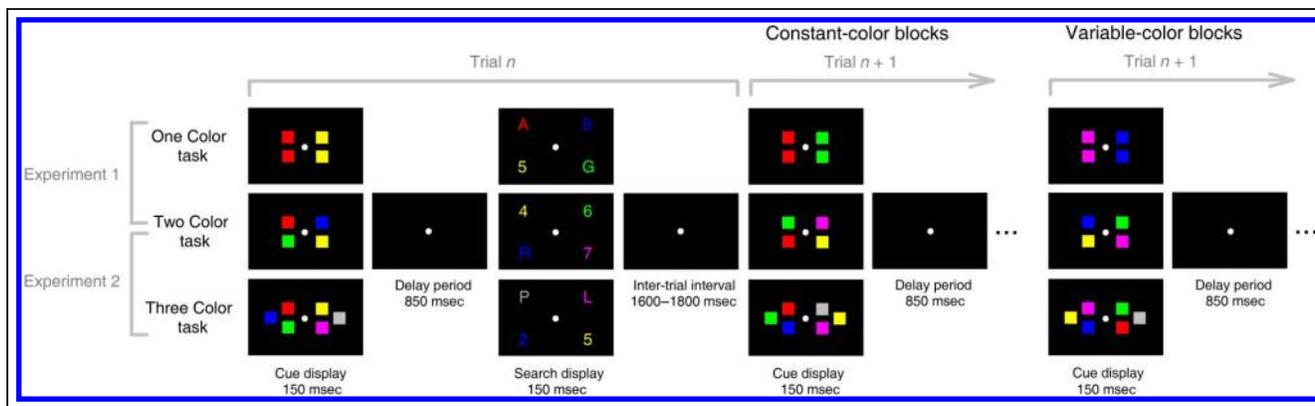
to reflect the spatially selective attentional processing of such objects in extrastriate visual cortex (e.g., Eimer & Kiss, 2008; Lien, Ruthruff, Goodin, & Remington, 2008; Hopf et al., 2000; Woodman & Luck, 1999; Eimer, 1996; Luck & Hillyard, 1994). In a recent N2pc study (Grubert & Eimer, in press), we used spatial cueing procedures similar to those employed by Irons et al. (2012). When observers searched for two possible target colors, target-matching color cues elicited reliable N2pc components whereas nontarget color cues did not. This provides direct electrophysiological evidence for the hypothesis that attentional task sets for multiple target colors can be activated simultaneously. In another N2pc study (Grubert & Eimer, 2013), observers searched for color-defined targets that were accompanied by a single gray nontarget object in the opposite visual field under conditions where targets were always defined by the same color (One Color task) or could have one of two equally likely colors (Two Color task). Reliable N2pc components were elicited by target objects not only in the One Color task but also in the Two Color task, in line with the presence of multiple color-specific search templates. In a third study (Grubert & Eimer, 2015), participants had to select two color-defined targets in two displays that were presented in rapid succession and were accompanied by a nontarget in a different task-irrelevant color on the opposite side. In different task conditions, the two targets were defined by the same constant color or by two different colors. In both tasks, N2pc components were elicited by targets in the first and second display, and their onset latency difference closely matched the objective onset asynchrony between the two displays (10 or 100 msec), suggesting that both targets were selected rapidly and in parallel, with each selection process following its own independent time course (see also Eimer & Grubert, 2014). The fact that this temporal pattern of N2pc components was observed when successively presented targets had two different colors again suggests that two color-specific templates can be active simultaneously. It should be noted that, in both experiments (Grubert & Eimer, 2013, 2015), there was a small but systematic target N2pc onset delay of about 20–30 msec when two colors were task-relevant relative to the One Color tasks, suggesting that the deployment of attention to a template-matching object is slightly faster during single-color as compared with multiple-color search. However, these N2pc delays during multiple-color search were interpreted to result from competitive interactions between two simultaneously activated attentional templates, rather than from the prioritisation of a single color-specific search template (Grubert & Eimer, 2015). Additional evidence for efficient attentional guidance by color target templates comes from a recent N2pc study (Christie, Livingstone, & McDonald, 2015) where observers searched for one of two possible color-defined targets that were presented among a variable number of distractors in different nontarget colors. Although RTs increased with increasing display set size, the onset latency of target

N2pc components remained unaffected by set size, again suggesting efficient attentional target selection during multiple-color search.

Although the majority of recent experiments investigating whether attentional target selection can be guided by only a single or by multiple task sets for target-defining features have supported multiple-template control, the question remains why other studies (e.g., Houtkamp & Roelfsema, 2009) indicated that only a single target template can be active at any given time. In all studies that provided behavioral or electrophysiological evidence for multiple simultaneously active search templates (e.g., Grubert & Eimer, 2013, 2015, in press; Irons et al., 2012; Moore & Weissman, 2010), target-defining features remained constant across entire blocks of trials. In contrast, the strongest evidence for single-template attentional control comes from experiments where target identity was varied between individual trials (Houtkamp & Roelfsema, 2009). This difference may have important consequences for the nature of the attentional templates that control attentional target selection. When target identity changes across successive trials, a new search template has to be activated on each individual trial, which makes it likely that such templates are represented in visual working memory. In contrast, when observers look for the same search target across a large number of trials, the search process becomes more automatized. Under such conditions, attentional templates may no longer be actively held in working memory but could instead be handed off to a different cognitively less demanding longer-term storage system (see Woodman, Carlisle, & Reinhart, 2013; Olivers et al., 2011, for further discussion). Electrophysiological evidence for such a transfer of search templates from working memory to long-term memory comes from studies that measured the contralateral delay activity (CDA). The CDA is elicited during the active maintenance of target representations in working memory (Vogel & Machizawa, 2004). In experiments where laterally presented cues specified the shape of target objects for an upcoming search task, CDA components emerged contralateral to these cues and were larger in size when cue displays specified two possible target shapes than when they indicated a single shape (e.g., Reinhart, Carlisle, & Woodman, 2014; Carlisle, Arita, Pardo, & Woodman, 2011). These CDA components were interpreted as reflecting the active maintenance of target representations in working memory. Critically, no reliable CDA was present when cues specified a single target shape and the identity of this target remained constant across blocks of trials, suggesting that target templates were no longer held in working memory but were transferred to a different long-term memory store (Carlisle et al., 2011). In these constant-shape blocks, CDA amplitudes decreased in size across the first few trials, indicating that this transfer of search templates to long-term storage takes place rapidly (see Gunseli, Olivers, & Meeter, 2014, for evidence that this CDA decrease can be observed both for easy and difficult search tasks).

The hypothesis that search templates are no longer represented in working memory but are transferred to a different long-term storage system when target features remain constant across trials is in line with previous evidence that search becomes automatized as a result of practice with constant but not with varied target mappings (Czerwinski, Lightfoot, & Shiffrin, 1992; Logan, 1988; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Once automatized, search for 10 possible targets may be as effective as search for a single target (e.g., Neisser, Novick, & Lazar, 1963), reflecting the essentially unlimited capacity of long-term storage. Because target colors were constant in previous behavioral and electrophysiological studies that found evidence for multiple color-specific task sets (e.g., Grubert & Eimer, 2013, 2015; Irons et al., 2012; Moore & Weissman, 2010), the search templates investigated in these studies may have been represented in long-term memory rather than working memory. Attentional control by multiple feature-specific templates may be possible with constant target mappings because such templates are held in an unlimited-capacity long-term memory store. In contrast, when target identity varies across trials and target templates are therefore held in working memory, activating simultaneous attentional task sets for multiple features may not be possible. The goal of this study was to test this hypothesis by comparing the efficiency of attentional target selection during single-color and multiple-color search under conditions where target color(s) either remained constant or varied across individual trials. Participants in Experiment 1 searched for targets defined by one or two possible colors (One Color vs. Two Color task) that were accompanied by three distractors in three different colors. In Experiment 2, they searched for two or three possible colors (Two vs. Three Color task). Similar to Carlisle et al. (2011), each search display was preceded by a lateralized cue display that specified the task-relevant color(s) for this particular trial (see Figure 1 for illustration). Critically, there were blocks where the target color(s) remained constant and blocks where these colors varied across trials. Each of the four combinations of color load (one vs. two in Experiment 1; two vs. three in Experiment 2) and color variability (constant vs. variable) was delivered in a set of successive experimental blocks.

To confirm that target templates in constant-color blocks were less likely to rely on working memory than in variable-color blocks, we recorded CDA components during the interval between cue and search displays at posterior electrodes contralateral to the side of the currently task-relevant items in the cue displays. In line with the findings of Carlisle et al. (2011), CDA components were expected to emerge in variable-color blocks and to increase in amplitude as a function of color load. If attentional templates are no longer held in working memory when target features remain unchanged across blocks of trials, no CDA components should be found at all in constant-color blocks. To assess our main research question regarding the speed and efficiency with which focal attention was



**Figure 1.** Schematic illustration of a constant-color and variable-color trial sequence in the One Color, Two Color, and Three Color tasks of Experiments 1 and 2. Each trial started with the presentation of a bilateral cue display, specifying one, two, or three possible target color(s) for the subsequent search display. The task-relevant side of the cue displays alternated between blocks (in the trials shown, the left side is task-relevant). Search displays were presented after a delay period and contained a target in one cued color and three nontargets in three different colors. Participants' task was to report whether the target-color item was a digit or a letter. In constant-color blocks, the target color(s) were fixed across all trials so that the cues always specified the same target color(s) for each search array. In variable-color blocks, the target colors changed from trial to trial, so that the cues showed a different (set of) target color(s) on each trial.

deployed to target objects in the actual search displays, we measured N2pc components elicited in response to the targets. If multiple color-specific attentional templates can be activated simultaneously when target colors remain constant but not when these colors vary across trials, target N2pc components should differ between constant-color and variable-color blocks during multiple-color search (Two and Three Color tasks). N2pc components should be elicited by target objects in constant-color blocks but should be strongly delayed or perhaps even entirely absent in variable-color blocks. Furthermore, the costs of increasing color load from one to two (Experiment 1) or from two to three (Experiment 2) should affect target N2pc amplitudes and latencies more strongly in variable-color relative to constant-color blocks.

## EXPERIMENT 1

### Methods

#### Participants

Fifteen paid participants were tested in Experiment 1 (aged 21–41 years, mean age = 30 years). Ten were women; three were left-handed. All participants had normal or corrected-to-normal vision and color vision (as verified with the Ishihara color vision test; Ishihara, 1972).

#### Stimuli and Procedure

Stimuli were presented on a 22-in. Samsung wide SincMaster 2233 LCD monitor with a 100-Hz refresh rate and at a resolution of 1280 × 1024 pixels. Participants were seated in a dimly illuminated test chamber, approximately 100 cm away from of the monitor. The Cogent 2000 toolbox ([www.vislab.ucl.ac.uk/Cogent/](http://www.vislab.ucl.ac.uk/Cogent/)) for MATLAB (The

MathWorks, Natick, MA) running under Windows XP on an LG Pentium PC was used for stimulus presentation, timing, and response recording. Two vertically aligned purpose-built response keys were employed to record manual responses.

All stimuli were presented against a black background. A gray fixation point ( $0.2^\circ \times 0.2^\circ$ ) was continuously present throughout each experimental block. Each trial started with the presentation of a cue display for 150 msec, which was followed by an 850-msec blank period and a search array that was displayed for 150 msec (see Figure 1). The intertrial interval between the offset of a search array and the onset of the cue display on the next trial was temporally jittered between 1600 and 1800 msec. Cue displays contained two sets of two vertically aligned colored squares, presented bilaterally to the left and right of fixation at a horizontal distance of  $0.8^\circ$  (measured relative to the center of each square). The size of each individual square was  $0.6^\circ$ . In each hemifield, one square was presented at a vertical distance of  $0.4^\circ$  above and the other below the horizontal meridian. In half of all blocks, the squares on the right side of the cue display determined the target color(s) for the upcoming search display. In the other half, the squares on the left side were task relevant. The side of the relevant color cue was alternated between blocks. Participants were informed about this task-relevant side by a written instruction on the computer screen that was presented at the start of each experimental block. Search displays contained four differently colored digits and letters. The size of each of these items was  $0.6^\circ \times 0.5^\circ$ . Each of them was presented in a different quadrant of the visual field at a distance of  $1^\circ$  from the vertical and horizontal meridian (with respect to the center of the stimulus). Digits (2, 4, 5, 6, 7, and 9) and capital letters (S, A, G, R, L, and P) were chosen randomly, without replacement, for each stimulus location in each

search display. Possible stimulus colors in both cue and search arrays were red (CIE color coordinates .627/.336), green (.263/.568), blue (.189/.193), yellow (.422/.468), and magenta (.289/.168). All colors were equiluminant ( $\sim 10.2 \text{ cd/m}^2$ ).

Participants' task was to find the search item in the color specified by the preceding cue display and to indicate its identity (digit or letter) with a left-hand or right-hand response. Key-to-category (top or bottom key for digit or letter) and hand-to-key assignments (left or right hand on top or bottom key) were counterbalanced across participants but remained constant for each participant throughout the experiment. There were four different task conditions for each of the four different combinations of color load (One Color task vs. Two Color task) and color variability (constant-color vs. variable-color conditions). These four conditions are illustrated in Figure 1. In the One Color task, both cue display items on one side had one particular target color (e.g., red). The two squares on the opposite side of the cue display had a different randomly assigned color. For the Two Color task, the five possible colors were combined into five sets of two target colors that were not adjacent in color space and therefore not linearly separable from the remaining nontarget colors (red and green, red and blue, green and magenta, blue and yellow, and yellow and magenta). The two cue display squares on the relevant side showed these two target colors, and the two squares on the opposite side showed two other randomly selected colors. The two colors on either side of the cue display were assigned randomly to the top and bottom square. Search arrays always contained four items in four different colors (one cued target color, the color/colors that appeared on the irrelevant side of the cue display, and one or two colors that did not appear in the cue display). Participants performed these One Color and Two Color tasks in two blocked variants. In the constant-color condition, the target colors were fixed across all trials so that the cues always specified the same upcoming target color(s) for each search array (e.g., red and green on Trial 1, red and green on Trial 2, red and green on Trial 3, etc.). The fixed target colors were counterbalanced across participants. Each of the five possible colors (red, green, blue, yellow, or magenta) for the One Color task and each of the five 2-color sets for the Two Color task was assigned to 3 of the 15 participants tested, with the restriction that there was no overlap between the target colors selected for the One and Two Color tasks. In the variable-color condition, the target colors changed from trial to trial, so that the cues showed a different (set of) target color(s) on each trial (e.g., red and green on Trial 1, blue and yellow on Trial 2, green and magenta on Trial 3, etc.). One of the five possible target colors (One Color task) or target color sets (Two Color task) was randomly chosen on each trial, and all colors were presented equally often as cues and targets within each block.

Each participant completed six successive blocks of 40 trials for each of the four task conditions, resulting in 24 blocks and 960 experimental trials in total. Each block contained 10 trials for each of the four target locations (top left, top right, bottom left, and bottom right) in the constant One Color task, two trials for each of the 20 combinations of target location and target color (red, green, blue, yellow, and magenta) in the variable One Color task, five trials for each of the eight combinations of target location and target color (one of the two colors from a fixed two-color set) in the constant Two Color task, and one trial for each of the 40 combinations of target location, target color (one of two possible target colors), and target color set (five possible two-color sets) in the variable Two Color task. The sequence of task conditions was counterbalanced across participants. Eight participants started with the variable-color condition (One Color task preceded by Two Color task for four participants, and vice versa for the other four). The other seven participants started Experiment 1 with the constant-color condition (One Color task preceded by Two Color task for four participants, and vice versa for the remaining three). For all participants, the order of the One Color and Two Color tasks was reversed between the two halves of the experiment. All participants received 20 practice trials of the variable One Color task before the start of the experimental blocks. No other training was provided during the experiment.

### *EEG Recording and Data Analysis*

The continuous EEG was DC-recorded from 27 scalp sites at standard positions of the extended 10/20 system, sampled at a rate of 500 Hz, and digitally low-pass filtered at 40 Hz. No further filters were applied after EEG acquisition. Impedances were kept below 5 k $\Omega$ . All electrodes were referenced to the left earlobe during recording and were rereferenced offline to the average of both earlobes. Trials with artifacts (eye movements exceeding  $\pm 30 \mu\text{V}$  in the HEOG channels; blinks exceeding  $\pm 60 \mu\text{V}$  at Fpz; muscular movements exceeding  $\pm 80 \mu\text{V}$  in all other channels), with incorrect, anticipatory (faster than 200 msec), very slow (slower than 1500 msec), or missing responses, were excluded from EEG analyses. For the remaining trials, EEG signals were segmented within two time intervals (from 100 msec before to 1000 msec after cue display onset, and from 100 msec before to 400 msec after search display onset) to compute CDA components to cue displays and N2pc components to search displays, respectively. Separate averages were computed for each of the four task conditions (constant and variable One Color and Two Color tasks), separately for trials where the item of interest (the task-relevant cue or the target) appeared in the left or right visual field. CDA amplitudes were quantified on the basis of mean amplitudes obtained in the 300–1000 msec time window after cue array onset at lateral posterior electrodes PO7 and PO8.

N2pc amplitudes were quantified on the basis of mean amplitudes obtained in the 200–300 msec time window after search array onset at the same lateral posterior electrodes. N2pc onset latencies were determined with a jackknife-based procedure (Ulrich & Miller, 2001; Miller, Patterson, & Ulrich, 1998) on the basis of difference waveforms obtained by subtracting ERPs at electrodes PO7/8 ipsilateral to the side of a target from contralateral ERPs. With this procedure, onset latencies are estimated on the basis of grand-averaged difference waves of 15 subsamples, obtained by successively excluding one participant from the original sample. N2pc onset latencies were computed separately for each task condition and were defined as the point in time when the difference waveform for each subsample exceeded an absolute threshold value of  $-1 \mu\text{V}$ . This absolute threshold was determined as half of the jackknifed peak amplitude of the smallest N2pc (the smallest N2pc in Experiment 1 was the constant Two Color N2pc with  $-2.0 \mu\text{V}$ ).  $F$  and  $t$  values of the statistical comparisons were corrected according to the formula described by Miller et al. (1998) and Ulrich and Miller (2001) and are indicated with the labels “ $F_c$ ” and “ $t_c$ ,” respectively. All  $t$  tests are two-tailed and Bonferroni-corrected where necessary. Effect sizes are reported in terms of Cohen’s  $d$  (Cohen, 1988), with a confidence interval of 95%, for  $t$  tests and partial eta squared ( $\eta_p^2$ ) for  $F$  tests and  $t$  test on jackknifed group means (jackknifed means were fed into one-way ANOVAs to allow for error variance correction according to the formula described by Ulrich & Miller, 2001). For all  $t$  tests on N2pc latency measures, effect sizes are reported as corrected partial eta squared (labeled  $\eta_{pc}^2$ ; see Grubert & Eimer, 2016, for identical procedures).

## Results

### Behavioral Results

We excluded 0.1% of all trials because of anticipatory (RTs < 200 msec) or very slow (RTs > 1500 msec) re-

sponses. Table 1 shows RTs and error rates for all four task conditions. Mean correct RTs were submitted to a repeated-measures ANOVA with the factors Color load (One Color, Two Color) and Color variability (constant-color, variable-color). A main effect of Color load,  $F(1, 14) = 146.3, p < .001, \eta_p^2 = 0.91$ , demonstrated that RTs were faster in the One Color (613 msec) relative to the Two Color task (745 msec). RTs were also faster in constant-color (646 msec) relative to variable-color trials (712 msec), as reflected in a main effect of Color variability,  $F(1, 14) = 25.0, p < .001, \eta_p^2 = 0.64$ . There was also a significant interaction between these two factors,  $F(1, 14) = 15.0, p = .002, \eta_p^2 = 0.52$ , as the RT delay in the Two Color task was larger in variable-color blocks than in constant-color blocks (158 msec vs. 105 msec). An ANOVA on error rates also revealed main effects of Color load,  $F(1, 14) = 29.1, p < .001, \eta_p^2 = 0.68$ , and Color variability,  $F(1, 14) = 29.2, p < .001, \eta_p^2 = 0.68$ , and an interaction,  $F(1, 14) = 12.8, p = .003, \eta_p^2 = 0.48$ . Errors were more frequent in the Two Color task relative to the One Color task (6.0% vs. 2.9%) and in variable-color relative to constant-color blocks (6.5% vs. 2.4%). The increase of error rates in the Two Color task relative to the One Color task was more pronounced in variable-color than in constant-color blocks (4.8% vs. 1.3%).

### CDA Components to Cue Displays

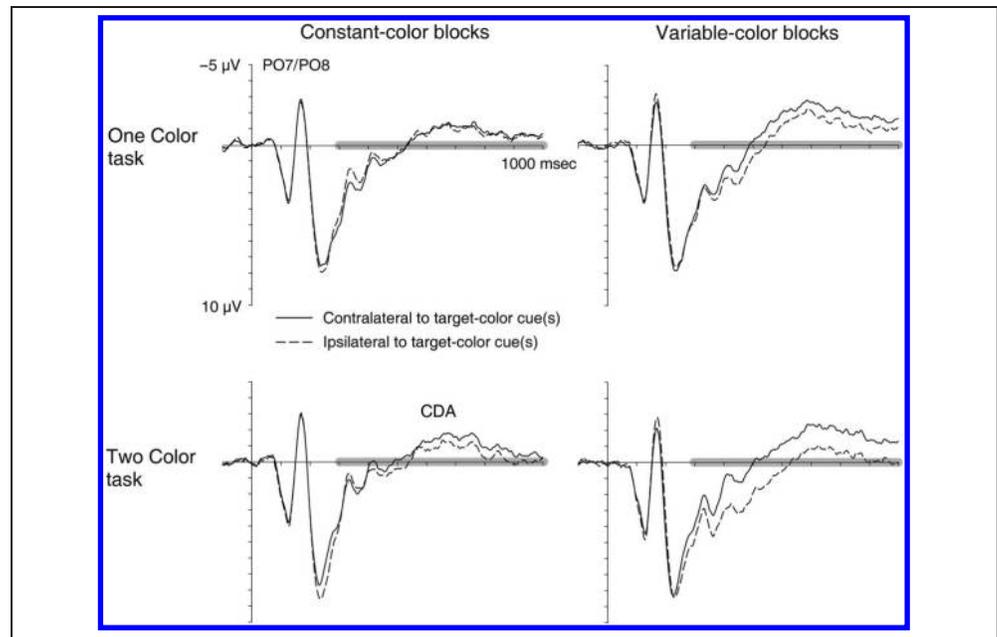
We examined CDA components to cue arrays to confirm that attentional control in constant-color blocks was less likely to rely on working memory target templates than in variable-color blocks. After exclusion of trials with artifacts, incorrect, anticipatory, very slow, or missing responses on average 80.7% of all trials remained in the analysis (ranging between 75.5% and 83.9% for the four task conditions). Figure 2 shows grand-averaged ERPs elicited at electrode sites PO7 and PO8 contra- and ipsilateral to the task-relevant color cues during the interval between cue and search displays, separately for the One

**Table 1.** RTs (in Milliseconds) and Error Rates (Percentage Correct) in the One Color, Two Color, and Three Color Tasks of Experiments 1 and 2, Separately for Constant-color and Variable-color Blocks

	<i>Constant-color Blocks</i>		<i>Variable-color Blocks</i>	
	<i>RTs (msec)</i>	<i>Error Rates (%)</i>	<i>RTs (msec)</i>	<i>Error Rates (%)</i>
<i>Experiment 1</i>				
One Color task	594 [83]	1.8 [1.3]	632 [93]	4.0 [3.7]
Two Color task	699 [104]	3.1 [2.6]	791 [133]	8.9 [4.6]
<i>Experiment 2</i>				
Two Color task	699 [86]	2.9 [2.7]	787 [96]	5.9 [3.5]
Three Color task	811 [109]	7.6 [5.5]	886 [82]	17.2 [7.6]

Square brackets specify standard deviations from the mean.

**Figure 2.** Cue-locked grand-averaged ERPs measured in constant-color blocks (left) and variable-color blocks (right) of the One Color (top) and Two Color tasks (bottom) of Experiment 1. ERPs are shown for the 1000-msec interval after cue array onset, at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the task-relevant target-color cues. CDA components were measured in the 300–1000 msec poststimulus interval (gray bar on *x* axis).



Color and Two Color tasks in constant-color and variable-color blocks. CDA components were larger in variable-color blocks relative to constant-color blocks and larger in the Two Color task than in the One Color task. This was confirmed by a repeated-measures ANOVA on ERP mean amplitudes measured in the 300–1000 msec window after cue display onset with the factors Color load, Color variability, and Laterality (electrode contralateral, ipsilateral to the task-relevant color cues). This analysis revealed a main effect of laterality,  $F(1, 14) = 33.2, p < .001, \eta_p^2 = 0.70$ , that interacted both with color load,  $F(1, 14) = 19.2, p = .001, \eta_p^2 = 0.58$ , and with color variability,  $F(1, 14) = 37.9, p < .001, \eta_p^2 = 0.73$ . There was no three-way interaction between laterality, color load, and color variability,  $F(1, 14) = 2.2, p = .163, \eta_p^2 = 0.13$ , indicating that the increase of CDA amplitudes in the Two Color relative to the One Color task was similar in variable-color and constant-color blocks. Follow-up *t* tests revealed that reliable CDA components were triggered in variable-color blocks both for the Two Color task ( $-1.5 \mu\text{V}; t(14) = 6.0, p < .001, d = .85$ ) and the One Color task ( $-0.7 \mu\text{V}; t(14) = 5.2, p < .001, d = .50$ ). In constant-color blocks, no reliable CDA was present in the One Color task ( $-0.1 \mu\text{V}; t(14) < 1$ ). However, a significant CDA was measured in the Two Color task ( $-0.4 \mu\text{V}; t(14) = 3.2, p = .006, d = .26$ ).

### *N2pc Components to Search Displays*

To address our main research question, we examined the N2pc component as a measure of the speed and efficiency of attentional deployment to target items in the search array. After trial exclusion, 89.3% of all trials remained in the analysis (ranging between 84.7% and 91.9% for the four task conditions). Figure 3 (top and middle) shows

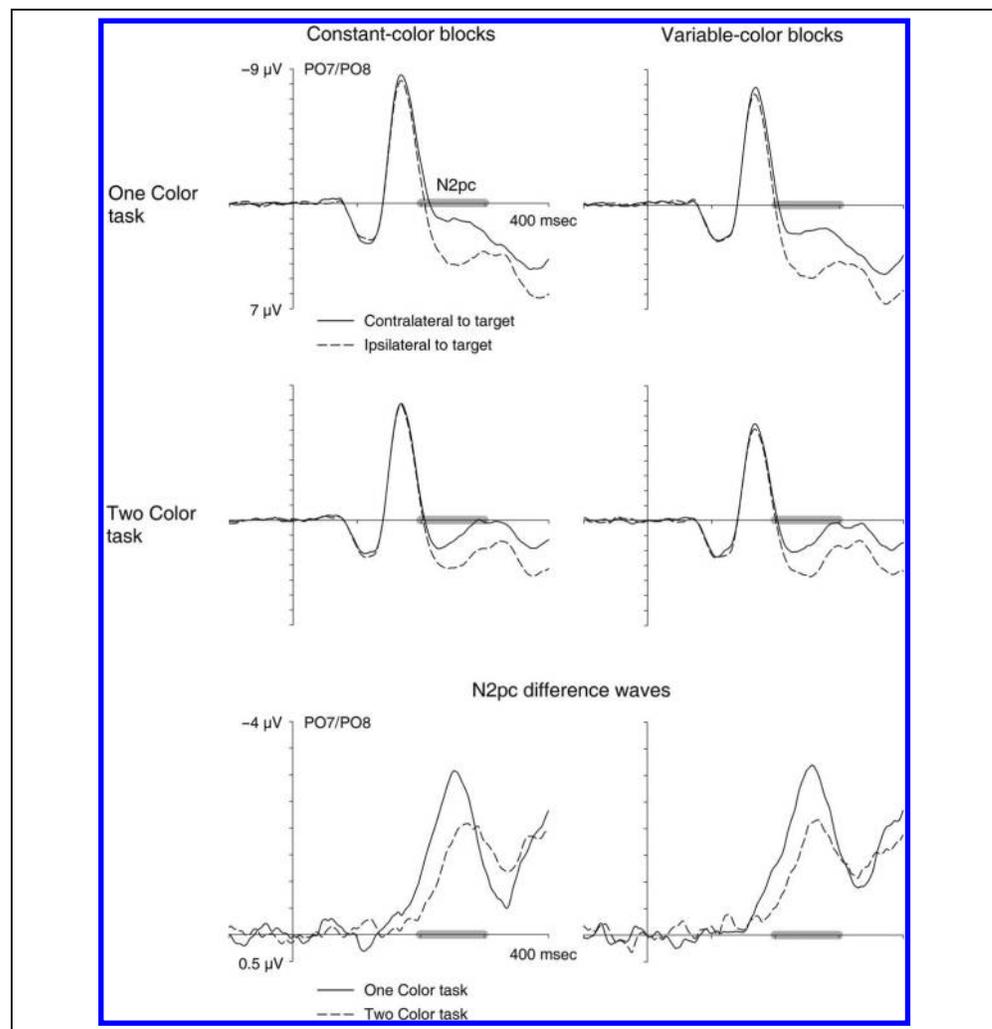
grand-averaged ERPs elicited at electrode sites PO7 and PO8 contra- and ipsilateral to the color-defined target item in the search array during the 400 msec after search display onset. These ERPs are shown separately for the One and Two Color tasks in blocks with constant or variable target colors. The panels on the bottom show N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs in the One Color and Two Color tasks for constant-color and variable-color blocks. Solid target N2pc components were triggered in all four task conditions, and these N2pcs were attenuated and delayed in the Two Color task relative to the One Color task. Importantly, these effects of color load on N2pc components appear very similar in constant-color and variable-color blocks. A repeated-measures ANOVA on N2pc mean amplitudes measured in the 200–300 msec time interval after search array onset, with the factors Color load, Color variability, and Laterality, confirmed this observation. A main effect of Laterality,  $F(1, 14) = 55.8, p < .001, \eta_p^2 = 0.80$ , was accompanied by an interaction of Color load and Laterality,  $F(1, 14) = 17.2, p = .001, \eta_p^2 = 0.55$ , reflecting the larger N2pc amplitudes in the One Color relative to the Two Color task ( $-2.3 \mu\text{V}$  vs.  $-1.5 \mu\text{V}$ ). There was no significant interaction between color variability and laterality,  $F(1, 14) = 2.3, p = .148, \eta_p^2 = 0.14$ , indicating that N2pc amplitudes did not differ systematically between constant-color and variable-color blocks. Critically, there was also no three-way interaction between Color load, Color variability, and Laterality,  $F(1, 14) < 1$ , which suggests that N2pc amplitude differences between the One and Two Color tasks were equivalent in constant-color and variable-color blocks. Follow-up *t* tests demonstrated that N2pc components of all four task conditions were reliably elicited, all  $t(14) > 5.5$ , all  $p < .001$ , all  $d > .32$ .

The N2pc latency differences between the One Color and Two Color tasks shown in the difference waveforms of Figure 3 were assessed with jackknife-based analyses. A repeated-measures ANOVA on N2pc onset latencies with the factors Color load and Color variability revealed a main effect of Color load,  $F_c(1, 14) = 33.4, p < .001, \eta_{pc}^2 = .70$ , as N2pc components emerged significantly earlier in the One Color relative to the Two Color task (194 msec vs. 225 msec). Most importantly, there was no interaction between Color load and Color variability,  $F_c(1, 14) < 1$ , indicating that this N2pc onset delay in the Two Color task was equivalent in constant-color and variable-color blocks. This was confirmed by two follow-up  $t$  tests, which showed that N2pc onset latency differences between the One and Two Color tasks were reliable and identical in size in constant-color (199 vs. 230 msec; +31 msec) and variable-color blocks (189 vs. 220 msec; +31 msec), both  $t_c(14) > 4.2$ , both  $p < .002$ , both  $\eta_{pc}^2 = .59$ . There was an unexpected tendency for N2pc components to emerge earlier in variable-color blocks, but the main effect of Color variability on N2pc onset latencies was not reliable,  $F_c(1, 14) = 4.2, p = .060, \eta_{pc}^2 = .23$ .

### Discussion of Experiment 1

The pattern of CDA components observed in Experiment 1 in response to cue displays was consistent with previous results by Carlisle et al. (2011). In variable-color blocks, reliable CDA components were elicited, and these components were larger in the Two Color task relative to the One Color task, reflecting the increased working memory load when participants prepare to search for two different possible target colors. In constant-color blocks, CDA components were much smaller, which suggests that target templates in working memory were less strongly activated when participants searched for the same target-defining features across many trials. As in Carlisle et al. (2011), there was no reliable CDA in constant One Color blocks. However, a small but significant CDA was observed in blocks where participants searched for two constant target colors (Figure 2). If search templates are always completely transferred to long-term memory when target features remain constant (e.g., Carlisle et al., 2011), CDA components should have been absent in constant-color blocks even when two colors were task-relevant.

**Figure 3.** Target-locked grand-averaged ERPs measured in constant-color blocks (left) and variable-color blocks (right) of the One Color (top) and Two Color tasks (middle) of Experiment 1. ERPs are shown in the 400-msec interval after search array onset at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the color-defined target item. The bottom panel shows N2pc difference waves obtained by subtracting ipsilateral from contralateral ERPs. N2pc components were measured in the 200–300 msec poststimulus interval (gray bar on x axis).



The presence of a significant CDA in constant Two Color blocks suggests that when memory load is increased, color-specific working memory representations remain activated to some degree. However, and most importantly, the strong attenuation of CDA components in constant-color relative to variable-color blocks suggests that target templates were stored in a different format in these two types of blocks. One possibility is that they were primarily held in long-term memory when target colors remained constant and in working memory when these colors were variable (see below for an alternative interpretation of the CDA differences between variable- and constant-color blocks).

However, the pattern of target N2pc results observed in Experiment 1 did not provide any evidence for qualitative differences in the guidance of attentional target selection by these two types of search templates. As can be seen in Figure 3 (bottom), color variability did not affect target N2pc components, which were virtually identical in constant-color and variable-color blocks. In contrast, increasing color load had a systematic effect. Target N2pcs emerged about 30 msec later in the Two Color relative to the One Color tasks, suggesting that the deployment of attention to template-matching objects was delayed when two color templates are simultaneously active (see Grubert & Eimer, 2013, 2015, for similar observations). N2pc components were also smaller during two-color as compared with one-color search, which indicates that the deployment of attention to template-matching target objects was less effective or more variable in time when color load was increased. In line with this interpretation, RTs were delayed by more than 130 msec in the Two Color task. The implications of these behavioral and electrophysiological costs of multiple-color search for the debate about simultaneous task sets for multiple features will be considered in the General Discussion.

The observation that the effects of increasing color load on the latency and amplitude of target N2pc components were essentially identical in constant-color and variable-color blocks is important, because it suggests that there are no systematic differences between search templates in working memory and in a longer-term memory store in their ability to guide attentional target selection. In sharp contrast to the hypothesis that templates in long-term memory facilitate efficient target selection during multiple-feature search whereas templates in working memory do not, the N2pc results of Experiment 1 suggest that there are no capacity differences between these two types of templates. It should be noted that the behavioral costs of increasing color load were larger with variable as compared with constant target mappings, in line with previous findings (e.g., Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In addition, there was also a general delay of RTs and an increase in error rates in variable-color as compared with constant-color blocks. As will be further considered in the General Discussion, these behavioral costs of variable target color mappings are likely to be generated at stages beyond

the initial allocation of attention to target objects, as reflected by the N2pc.

It is possible that Experiment 1 did not find any electrophysiological difference in template-guided target selection processes between constant-color and variable-color blocks because of the limited capacity demands of the Two Color task. If search templates in working memory were not strictly limited to a single feature but were able to represent up to two target features at the same time, this may have diluted any differences between the effects of long-term and working memory templates in this task. Such differences should however emerge in search tasks where more than two features are potentially task-relevant. In fact, Schneider and Shiffrin (1977) found that the costs of varied mappings on visual search performance increase with the number of possible target items. This possibility was tested in Experiment 2, which used the same procedures as Experiment 1, except that the One Color task was replaced by a Three Color task where participants had to find targets in one of three possible colors. As before, target colors remained the same in constant-color blocks but changed across individual trials in variable-color blocks. If the costs of variable target mappings on template-guided attentional selection processes only emerge with higher memory load, such costs should be evident for the Three Color task relative to the Two Color task in Experiment 2.

## EXPERIMENT 2

### Methods

#### *Participants*

Sixteen observers were paid to participate in Experiment 2. One participant was excluded from the sample because of excessive eye activity, resulting in a loss of more than 90% of all trials during artefact rejection. The remaining 15 participants were aged between 24 and 41 years (mean age = 31 years). Nine were women; three were left-handed. All participants had normal or corrected-to-normal vision and color vision (as verified with the Ishihara color vision test; Ishihara, 1972).

#### *Stimuli and Procedure*

Procedures were the same as in Experiment 1, except as stated below. Four different task conditions were run, and two of them (the constant and variable Two Color tasks) were identical to Experiment 1. In the other two task conditions, participants performed a constant or variable Three Color task where the target item in the search display could have one of three equally likely target colors (e.g., red, green, or blue). In this task, the bilateral cue arrays contained two sets of three differently colored squares. The two vertically aligned squares on each side appeared in the same locations as in the Two Color task, but they were now accompanied by an additional square

that appeared at a horizontal distance of  $1.9^\circ$  from fixation (measured relative to the center of this square; see Figure 1). As in the Two Color task, one of these sets of colored squares indicated the possible target colors for the upcoming search array, and the side of these task-relevant squares was alternated between blocks. As in Experiment 1, participants' task was to identify the category (digit, letter) of the search display item that matched one of the cued target colors. The set of five possible target-defining colors and the assignment of target colors in the Two Color task were identical to Experiment 1. In the constant-color Three Color task, each participant searched for those three colors that did not serve as their target colors in the constant-color Two Color task. This procedure resulted in five possible constant three-color target sets (red, blue, and yellow; red, green, and blue; red, green, and magenta; green, yellow, and magenta; and blue, yellow, and magenta). In the variable-color Three Color task, one of these three-color target sets was selected randomly on each trial. Distractor colors in both cue and search arrays were chosen randomly from the set of currently task-irrelevant colors. This set contained an additional equiluminant gray (CIE color coordinates .323/.353;  $\sim 10.2$  cd/m<sup>2</sup>), which was necessary to avoid distractor color repetition in the Three Color task.

As in Experiment 1, each participant completed six successive blocks of 40 trials for the constant and variable Two Color task, respectively. For the constant and variable Three Color task, they were tested in four consecutive blocks each, with 60 trials per block. Each constant-color block in the Three Color task contained five trials for each of the 12 combinations of target location (top left, top right, bottom left, and bottom right) and target color (one of three possible target colors). Each variable-color block contained one trial for each of the 60 combinations of target location, target color, and color set (five possible three-color sets). Counterbalancing of task conditions was identical to Experiment 1. Before the first experimental block, participants completed 20 practice trials of the variable-color Two Color task.

### EEG Recording and Data Analysis

Those were identical to Experiment 1, except that N2pc onset latencies were defined as the point in time when the difference waveform for each subsample exceeded an absolute threshold value of  $-0.6$   $\mu$ V (50% of the smallest jackknifed N2pc peak amplitude, which was  $-1.2$   $\mu$ V in the variable Three Color task).

## Results

### Behavioral Results

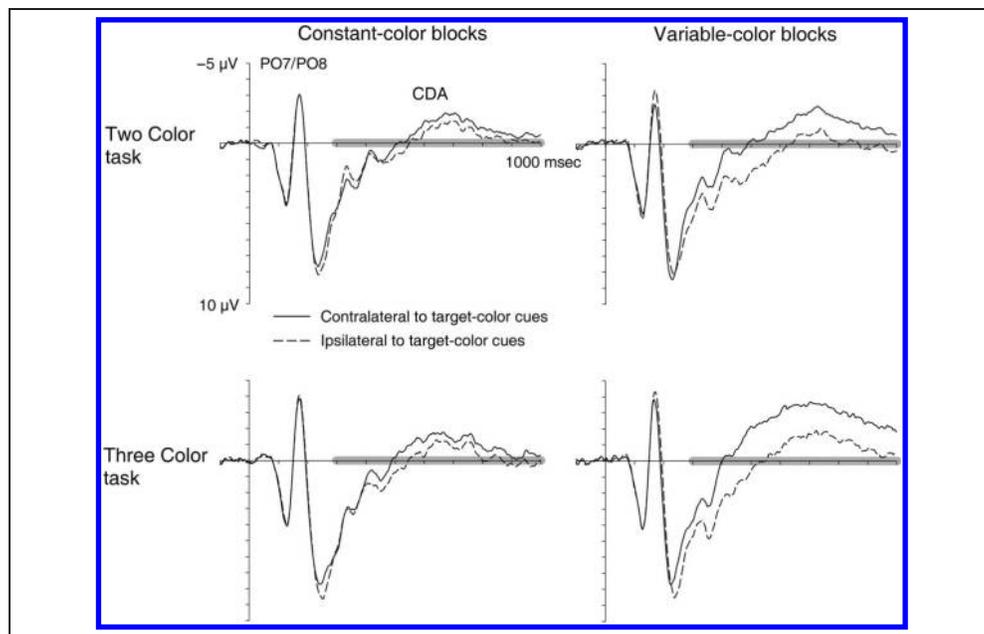
We excluded 1.8% of all trials were excluded because of anticipatory (RTs < 200 msec) or very slow (RTs > 1500 msec) responses. Table 1 shows RTs and error rates for all four

task conditions. A repeated-measures ANOVA with the factors Color load (Two Color, Three Color) and Color variability (constant-color, variable-color) on mean correct RTs revealed a main effect of Color load,  $F(1, 14) = 72.2$ ,  $p < .001$ ,  $\eta_p^2 = 0.84$ , with faster RTs in the Two Color task relative to the Three Color task (743 msec vs. 848 msec), as well as a main effect of Color variability,  $F(1, 14) = 23.5$ ,  $p < .001$ ,  $\eta_p^2 = 0.63$ , reflecting faster responses in constant-color relative to variable-color blocks (755 msec vs. 836 msec). There was no interaction between these two factors,  $F(1, 14) < 1$ , indicating that the effects of increased color load on RTs did not differ systematically between constant-color blocks (112 msec) and variable-color blocks (99 msec). For error rates, the same overall pattern was observed. There were main effects of Color load,  $F(1, 14) = 49.7$ ,  $p < .001$ ,  $\eta_p^2 = 0.78$ , and Color variability,  $F(1, 14) = 37.9$ ,  $p < .001$ ,  $\eta_p^2 = 0.73$ , with more incorrect responses in the Three Color as compared with the Two Color task (12.4% vs. 4.4%), and in variable-color as compared with constant-color blocks (11.6% vs. 5.2%). An interaction between these two factors,  $F(1, 14) = 24.4$ ,  $p < .001$ ,  $\eta_p^2 = 0.64$ , was due to the fact that the increase in error rates in the Three Color relative to the Two Color task was more pronounced on variable-color blocks (11.3%) than in constant-color blocks (4.6%).

### CDA Components to Cue Displays

A total of 75.4% of all trials remained in the analysis after the exclusion of trials with errors or artifacts and slow, fast, or missing responses (ranging between 71.3% and 79.9% for the four task conditions). Figure 4 shows grand-averaged ERPs elicited at PO7/8 contra- and ipsilateral to the task-relevant color cues during the interval between cue and search displays, separately for the Two and Three Color tasks in constant-color and variable-color blocks. As in Experiment 1, CDA components were generally larger in variable-color blocks than in constant-color blocks, although a CDA also appears to be present in blocks with two or three constant target colors. Furthermore, increasing the color load from two to three resulted in the expected increase of CDA amplitudes. A repeated-measures ANOVA on ERP mean amplitudes measured in the 300–1000 msec window after cue display onset with the factors Color load, Color variability, and Laterality revealed a main effect of Laterality,  $F(1, 14) = 47.1$ ,  $p < .001$ ,  $\eta_p^2 = 0.77$ , that interacted with Color variability,  $F(1, 14) = 40.5$ ,  $p < .001$ ,  $\eta_p^2 = 0.74$ , thus confirming the observation that CDA components were larger in variable-color blocks. There was also an interaction between Color load and Laterality,  $F(1, 14) = 11.3$ ,  $p = .005$ ,  $\eta_p^2 = 0.45$ , reflecting the increase of CDA amplitudes in Three Color as compared with Two Color blocks. As in Experiment 1, there was no three-way interaction between Laterality, Color load, and Color variability,  $F(1, 14) = 2.3$ ,  $p = .152$ ,  $\eta_p^2 = 0.14$ , indicating that the increase of CDA amplitudes with increased color load did not differ between variable-color

**Figure 4.** Cue-locked grand-averaged ERPs measured in constant-color blocks (left) and variable-color blocks (right) of the Two Color (top) and Three Color tasks (bottom) of Experiment 2. ERPs are shown for the 1000-msec interval after cue array onset at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the task-relevant target-color cues. CDA components were measured in the 300–1000 msec poststimulus interval (gray bar on  $x$  axis).



and constant-color blocks. Follow-up  $t$  tests confirmed the presence of reliable CDA components in variable-color blocks ( $-1.4$  and  $-2.0$   $\mu\text{V}$  for the Two and Three Color tasks) as well as in constant-color blocks ( $-0.3$  and  $-0.6$   $\mu\text{V}$  for the Two and Three Color tasks), all  $t(14) > 3.0$ , all  $p < .009$ , all  $d > .18$ .

### *N2pc Components to Search Displays*

After trial exclusion, 80.0% of all trials remained in the analysis (ranging between 70.6% and 86.1% for the four task conditions). Figure 5 (top and middle) shows grand-averaged ERPs elicited at PO7/8 contra- and ipsilateral to the color-defined target item during the 400 msec after search display onset, separately for the Two and Three Color tasks, and blocks with constant or variable target colors. The corresponding N2pc difference waveforms in the Two Color and Three Color tasks are shown in the bottom panels, separately for constant-color and variable-color blocks. N2pc components were again solid in all four task conditions but were attenuated and delayed in the Three Color task relative to the Two Color task. Importantly, and analogous to Experiment 1, these effects of color load on target N2pc component were similar in constant-color and variable-color blocks. A repeated-measures ANOVA on N2pc mean amplitudes measured in the 200–300 msec time interval after search array onset with the factors Color load, Color variability, and Laterality obtained a main effect of Laterality,  $F(1, 14) = 50.2$ ,  $p < .001$ ,  $\eta_p^2 = 0.78$ , as well as an interaction between Color load and Laterality,  $F(1, 14) = 11.0$ ,  $p = .005$ ,  $\eta_p^2 = 0.44$ . This was due to the fact that N2pc components were larger in the Two Color relative to Three Color task ( $-1.4$   $\mu\text{V}$  vs.  $-0.9$   $\mu\text{V}$ ). There was no significant interaction between Color variability and Laterality,  $F(1, 14) = 1.7$ ,  $p = .217$ ,

$\eta_p^2 = 0.11$ , demonstrating that as in Experiment 1, there were no systematic N2pc amplitude differences between constant-color and variable-color blocks. Most importantly, the absence of a three-way interaction between Color load, Color variability, and Laterality,  $F(1, 14) = 1.2$ ,  $p = .301$ ,  $\eta_p^2 = 0.08$ , indicated that the reduction of N2pc amplitudes with the increase in color load was the same in constant- and variable-color blocks. Follow-up  $t$  test confirmed that reliable N2pc components were present in all four task conditions, all  $t(14) > 3.3$ , all  $p < .005$ , all  $d > .26$ . The N2pc onset delay in the Three Color task relative to the Two Color task that is evident in the difference waves of Figure 5 was assessed with jackknife-based analyses. There was a main effect of Color load,  $F_c(1, 14) = 12.8$ ,  $p = .003$ ,  $\eta_{pc}^2 = .48$ , confirming that the N2pc emerged later in the Three Color task than in the Two Color task (226 msec vs. 207 msec). There was no main effect of Color variability, and no interaction between Color load and Color variability, both  $F_c(1, 14) < 1$ , indicating that N2pc onset latencies did not differ between constant-color and variable-color blocks. Follow-up  $t$  tests showed that the N2pc onset delay in the Three Color relative to the Two Color task was reliably present both in constant-color blocks (226 msec vs. 209 msec; +17 msec) and in variable-color blocks (226 msec vs. 204 msec; +22 msec), both  $t_c(14) > 2.3$ , both  $p < .033$ , both  $\eta_{pc}^2 > .28$ .

### **Discussion of Experiment 2**

The results obtained in Experiment 2 were very similar to Experiment 1. Again, CDA amplitudes measured in response to cue displays were much larger in variable-color relative to constant-color blocks, indicating that search templates in working memory were more strongly activated when target colors changed between trials and that

these templates were at least partially transferred to long-term memory in blocks with constant target colors. In variable-color blocks, CDA components were larger for the Three Color task as compared with the Two Color task, reflecting the difference between the retention of three versus two possible target colors in working memory. As in Experiment 1, a small but reliable CDA was present in constant-color blocks for the Two Color task, and this component was larger in the Three Color task (Figure 4). This again suggests that target representations are not completely handed off to long-term memory when target features remain constant, but that search templates in working memory are still activated to some degree under these conditions, in particular when memory load is high.

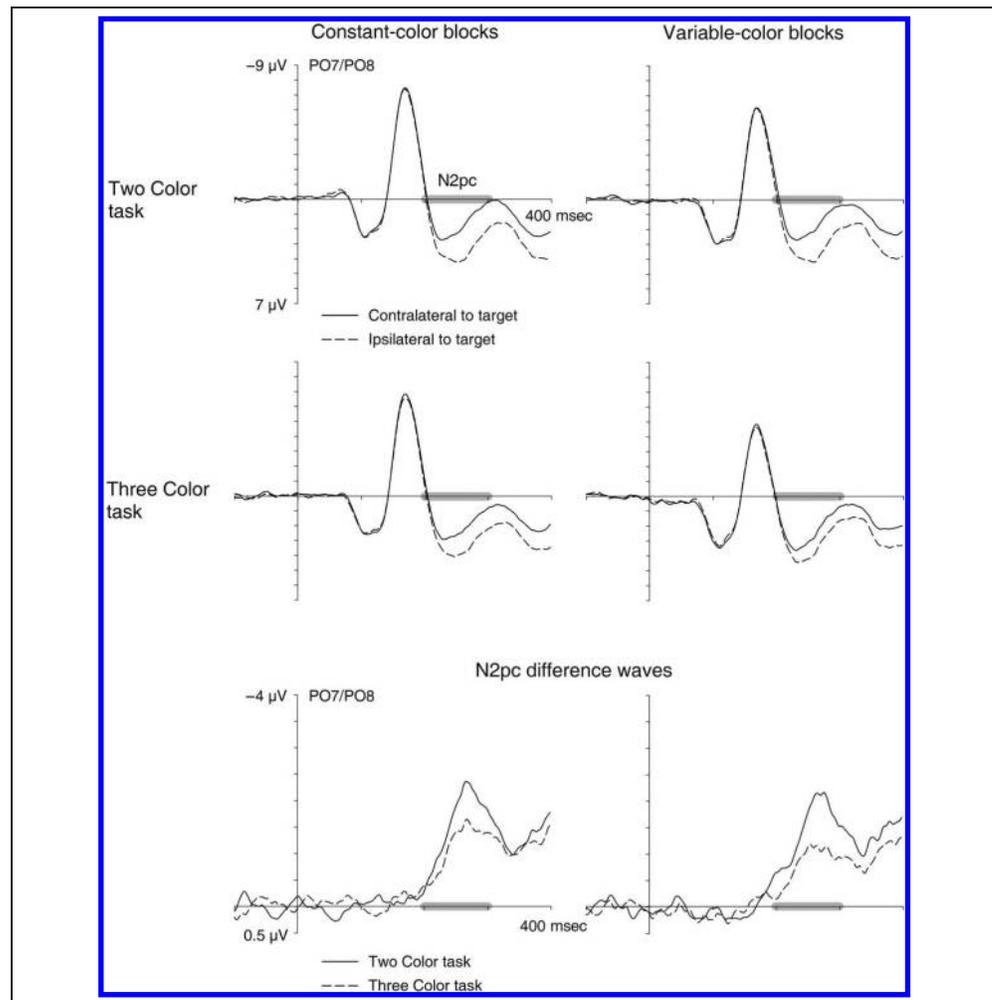
Most importantly, the pattern of N2pc components to target objects in constant-color and variable-color blocks confirmed the observations of Experiment 1. Again, there were no systematic N2pc differences between these two types of blocks (see Figure 5, bottom). In both constant-color and variable color-blocks, N2pc components were attenuated and emerged about 20 msec later when participants searched for three as compared with two possible target colors, demonstrating that the increase of color

memory load slightly impaired the allocation of attention to target objects. The fact that this delay did not differ between constant-color and variable-color blocks in Experiment 2 again suggests that there are no systematic differences between the capacity of target templates in long-term and working memory. As in Experiment 1, these electrophysiological results contrasted with the effects of color variability on behavioral performance, with slower RTs and increased error rates in variable-color blocks and a much steeper increase in error rates for the Three Color versus Two Color task in these blocks relative to constant-color blocks.

## GENERAL DISCUSSION

The goal of this study was to find out whether the deployment of attention to target objects during multiple-color search is more efficient when target-defining colors remain constant than when they vary across trials. We compared the guidance of attentional target selection by multiple-color templates in blocks where target colors were constant and could thus be represented in long-term memory and blocks where they were variable and therefore had to be held in working memory. Target

**Figure 5.** Target-locked grand-averaged ERPs measured in constant-color blocks (left) and variable-color blocks (right) of the Two Color (top) and Three Color tasks (middle) of Experiment 2. ERPs are shown in the 400-msec interval after search array onset at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the color-defined target item. The bottom panel shows N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. N2pc components were measured in the 200–300 msec poststimulus interval (gray bar on x axis).



colors (one vs. two in Experiment 1, two vs. three in Experiment 2) were specified by cue displays that preceded search displays on each trial, and these colors either remained the same in successive blocks or varied across individual trials.

In both experiments, CDA components elicited in the interval between cue and target displays were substantially larger in variable-color than in constant-color blocks. The fact that CDA amplitudes in variable-color blocks increased when memory load was increased from one to two colors (Experiment 1) and from two to three colors (Experiment 2) demonstrates that multiple target-defining colors were simultaneously maintained in working memory. The observation that a small but reliable CDA component was present when participants searched for two constant target colors and the fact that this component was even larger during constant three-color search suggest that target templates may still rely on working memory when target-defining features remain constant for an extended period. This could either be due to the reliance on working memory for some proportion of all trials or the parallel use of working memory and long-term memory representations of target features. Recently, Reinhart and Woodman (2014) have shown that participants reactivate working memory templates during high-reward trials, suggesting that driving attention from both long-term and working memory may be a strategic choice to improve performance.

The fact that CDA amplitudes were larger in variable-color relative to constant-color blocks demonstrates that there were systematic differences between the target templates that guided attentional target selection in these two types of blocks. The reduction of CDA components in constant-color blocks suggests that attentional guidance is primarily based on search templates in long-term memory in these blocks, whereas target representations in working memory are responsible for the control of attentional target selection in tasks with variable target colors. According to this hypothesis, the attenuation of CDAs in constant-color blocks would reflect a transfer of representations of target-defining features from working memory to a different memory store (e.g., long-term memory) that does not give rise to CDA components (e.g., Woodman et al., 2013; Carlisle et al., 2011). However, there are alternative accounts of the reduction of CDA amplitudes in constant-color relative to variable-color blocks. For example, it is possible that target templates in working memory were activated in both types of blocks, but in a different format. When target colors are not known in advance, observers have to attend to and encode color signals from the task-relevant side of the cue display on every trial, which is likely to result in strongly lateralized working memory representations that reflect the involvement of spatial attention during encoding. In constant-color blocks, observers rely less on spatially selective encoding of specific cue colors on each trial, because representations of target colors can be centrally generated and maintained. Here,

these representations may be less lateralized, but still held in working memory. Because the CDA only reflects the amount of lateralized visual information that is currently maintained in working memory, the reduction of CDA amplitudes in constant-color blocks is consistent with this alternative interpretation.

If repeatedly searching for the same set of target features results in an automatization of the search process (e.g., Schneider & Shiffrin, 1977) that is linked to a transfer of search templates from capacity-limited working memory to a long-term memory store with unlimited capacity (e.g., Carlisle et al., 2011), template-guided attentional target selection during multiple-color search should have been much more efficient in constant-color as compared with variable-color blocks. The pattern of target N2pc results obtained in this study did not support this hypothesis. N2pc components to color-defined search targets were virtually identical in constant-color and variable-color blocks, and this was not only the case for the One Color task but also for the Two Color and Three Color tasks. Increasing the number of possible target colors from one to two (Experiment 1) or from two to three (Experiment 2) resulted in significantly delayed and attenuated N2pc components, demonstrating systematic costs of color load on the deployment of attention to target objects (see below for further discussion). Critically, these costs were virtually identical in constant-color and variable-color blocks, and this was the case in both experiments. If target templates are held in working memory in variable-color blocks and in long-term memory in constant-color blocks, the absence of any load-dependent N2pc differences between these blocks indicates that these two types of templates are equivalent in their capacity and thus in their ability to guide attention toward the location of target objects during single-color and multiple-color search.<sup>1</sup> Alternatively, this pattern of N2pc results might suggest that target templates were maintained in working memory in both constant and variable target colors, but in a different spatial format (see above).

In contrast to the absence of any differential effects of color variability on target N2pc components, behavioral performance was strongly affected when target colors varied across trials. There was a substantial RT delay in variable-color relative to constant-color blocks (65 msec in Experiment 1 and 81 msec in Experiment 2) that was accompanied by a corresponding increase in error rates (4.0% and 6.3%, respectively), in line with previous observations from visual search studies that compared constant and variable target mappings (e.g., Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In addition, the behavioral costs produced by increasing color load were more pronounced in variable-color blocks. This was the case both for RTs and error rates in Experiment 1 and only for error rates in Experiment 2. Given the absence of any N2pc differences between constant-color and variable-color blocks, these performance costs must be generated at processing stages beyond the rapid

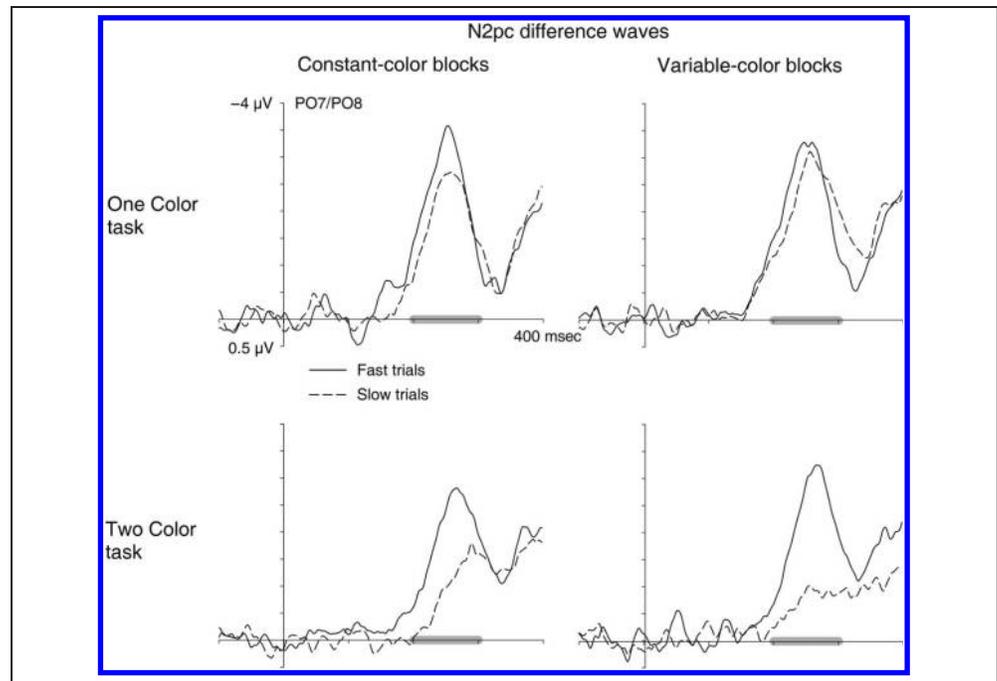
allocation of spatial attention to template-matching objects that is reflected by the N2pc. Shiffrin and Schneider (1977) distinguish three successive processes that jointly contribute to the automatization of search processes with constant target mappings—the rapid allocation of attention to target-matching features in a search display, the subsequent identification of a target object that is based on a comparison with a stored representation of target-defining features, and the selection of the response assigned to this particular target. The N2pc results obtained in this study strongly suggest that the first of these three processes (i.e., the attentional selection of target features) was not selectively impaired with variable as compared with constant target mappings. Because the target-defining dimension (color) differed from the response-relevant dimension (alphanumeric category) in this study, it is unlikely that response-related processes were responsible for the behavioral costs observed in variable-color blocks. This leaves the target identification process specified by Shiffrin and Schneider (1977) as the main source of these costs. Target selection and target identification are dissociable processes during visual search (e.g., Wolfe, 2007; see also Eimer, 2014, 2015, for further discussion), with identification depending on a comparison between the visual features of a selected object and a currently active target template. In line with Shiffrin and Schneider (1977), this comparison process may operate less rapidly and accurately when possible target features change across trials, in particular when multiple features are simultaneously task-relevant, and this could account for the pattern of behavioral costs in variable-color blocks.<sup>2</sup>

In contrast to color variability, color load had a reliable effect on target N2pc components in the present experiments. N2pc components were attenuated and delayed during search for two versus one possible target colors in Experiment 1, and an additional N2pc attenuation and delay was observed for the Three Color task in Experiment 2. These results demonstrate impairments in the deployment of spatial attention to target objects during multiple-color search independently of whether target templates were held in working or long-term memory. It is notable that the onset delay of N2pc components in the Two Color versus One Color tasks of Experiment 1 (31 msec) and in the Three Color versus Two Color tasks of Experiment 2 (19 msec) was much smaller than the corresponding difference of target RTs between these tasks (132 and 106 msec, respectively), which suggests that a delayed allocation of attention to target objects was only partially responsible for the RT costs during multiple-color search. Although the pattern of delayed N2pc onsets was similar to the N2pc delays observed in our previous experiments (Grubert & Eimer, 2013, 2015), target N2pc components were also attenuated for two-color versus one-color search, and for three-color versus two-color search in this study (see Figures 3 and 5, bottom). This attenuation suggests that attention may not have been deployed at all to color-defined search targets

within the N2pc time window on a substantial number of trials when two or three colors were task-relevant. To investigate this possibility, N2pc components measured in Experiment 1 were computed separately for trials with fast and slow target responses, based on RT median splits performed for each individual participant, and for each of the four combinations of color load and color variability. Figure 6 shows N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs on trials with fast and slow RTs, separately for the One and Two Color tasks in variable-color and constant-color blocks. In the One Color task, clear target N2pc components were present both for trials with fast and slow responses, and there were no significant N2pc amplitude differences between these trials, both  $t(14) < 1.6$ , both  $p > .13$ . This shows that attention was rapidly deployed to the search target on the vast majority of all trials during single-color search. In the Two Color task, large N2ps were present on fast response trials, but these components were reliably attenuated on trials with slow RTs, both in constant-color and variable-color blocks, both  $t(14) > 5.3$ , both  $t < .001$ , both  $d > 1$ . This demonstrates that on a substantial number of Two Color trials, the allocation of attention to the color-defined target object was considerably delayed, resulting in slow target discrimination responses on these trials.

What do these observations imply for the issue of attentional templates for multiple target features? If such templates are activated simultaneously during search for multiple possible target colors, they should be able to guide attention efficiently to color-defined target objects. The marked attenuation of target N2pcs during multiple-color search observed in this study, in particular for trials with slow responses, suggests instead that representations of target-defining colors were either not fully activated during the preparation for an upcoming search display or not always effective in controlling the subsequent deployment of attention to color-matching objects. The observation that CDA components elicited in response to cue displays in variable-color blocks were larger when these cues specified two target colors rather than a single color and larger still in the Three Color task indicates that all target-defining colors were represented simultaneously in working memory. However, the attenuation of target N2pc components during multiple-color search demonstrates that the guidance of attention by these representations was less effective than during search for a single target color. To provide further support for this hypothesis, CDA components measured in the Variable Two Color task of Experiment 1 were computed separately for trials with fast versus slow responses. There were no systematic CDA amplitude differences between these two types of trials,  $F(1, 14) < 1$ , indicating that the reduction of target N2pc components on slow response trials was not linked to insufficient color-specific preparation but instead to impaired attentional guidance by target color templates during multiple-color search. It is possible

**Figure 6.** N2pc difference waveforms in variable-color and constant-color blocks of the One Color and Two Color tasks of Experiment 1, shown separately for trials with fast and slow RTs (based on RT median splits performed for each individual participant and task condition).



that, although all target colors were stored in memory, only one of these was actively prioritized and thus able to control the subsequent deployment of attention, whereas the others were less active “accessory items” (e.g., Olivers et al., 2011) and had no impact on attentional target selection processes. This hypothesis that only a single color-specific attentional template can be activated on any given trial predicts that relative to single-color search, N2pc components during the Two Color task of Experiment 1 should be reduced in size by 50%, because a target-color item would match the currently active search template on only half of all trials. In fact, the target N2pc amplitudes decreased only by about 35% between the One Color and Two Color tasks (averaged across variable-color and constant-color blocks), suggesting that on a subset of two-color search trials, templates for both target colors were active. Thus, the current findings do not provide clear-cut electrophysiological support for the single-template hypothesis. They do however demonstrate that the allocation of attention to target objects during multiple-color as compared with single-color search is impaired, which challenges the assumption that multiple feature-specific attentional task sets can be activated simultaneously without mutual interference (see Grubert & Eimer, 2015, for a similar suggestion).

The impaired attentional target selection during multiple-color search observed in this study even when target colors remained constant may appear inconsistent with previous behavioral and electrophysiological studies, which have found evidence for simultaneous attentional task sets for multiple colors (e.g., Grubert & Eimer, 2013, 2015, in press; Irons et al., 2012; Moore & Weissman, 2010). It is, however, notable that in all of these experiments, the demands on color-based attentional selectivity were generally

very low. The cue displays employed by Irons et al. (2012) and Grubert and Eimer (in press) always contained one color singleton item among uniform white or gray items. In the N2pc experiments by Grubert and Eimer (2013, 2015), individual stimulus displays only included two items on opposite sides. Moore and Weissman (2010) presented three objects in each stimulus display, but target objects always appeared at fixation, obviating the need for any color-based spatial selection. In contrast, there were always four objects in four colors in the search displays that were employed in the current study. Although this stimulus set size is relatively small when compared with standard behavioral visual search experiments, the fact that four different colors were present in each search display required that participants adopted a highly selective task set for the color(s) that were currently task-relevant to find the target object. It is possible that attentional sets for multiple colors are relatively effective in guiding attention in tasks where the color-based spatial selection of individual objects is easy and that the limitations of such task sets only become apparent when these task demands are increased. This needs to be investigated more systematically in future research.

In summary, the current study investigated template-guided attentional selection processes in single-color and multiple-color search and found no evidence for systematic differences between tasks where target colors remained constant and tasks where they varied across trials. The costs of increasing color memory load on attentional target selection were identical for both types of search tasks. If target templates are represented in working memory when target features are variable and in long-term memory when they are constant, these results suggest that the efficiency of attentional guidance by

both types of representations is equally impaired during multiple-color as compared with single-color search.

## Acknowledgments

This research was supported by grant ES/K006142/1 from the Economic and Social Research Council (ESRC), United Kingdom.

Reprint requests should be sent to Anna Grubert, Department of Psychological Sciences, Birkbeck, University of London, Malet Street, London WC1E 7HX, UK, or via e-mail: a.grubert@bbk.ac.uk.

## Notes

1. The fact that the absence of an interaction between Color load and Color variability for N2pc amplitudes and onset latencies in Experiment 1 for Loads 1 and 2 was confirmed in Experiment 2 for Loads 2 and 3 provides strong support for our conclusion that there are no systematic capacity differences between search templates in working and long-term memory. Because this conclusion is, however, based on the absence of predicted interactions rather than the presence of statistically significant differences, we performed additional Bayesian analyses to provide additional positive evidence for the hypothesis that these two types of templates are equivalent in terms of their capacity. Scaled JZS Bayes factors ( $B_{01}$  values specifying the strength of evidence in favor of the null hypothesis) were computed on the basis of  $t$  values from paired  $t$  tests (see Rouder, Speckman, Sun, Morey, & Iverson, 2009, for methodological details). These  $t$  tests compared effects of Color load (Load 2–Load 1 in Experiment 1; Load 3–Load 2 in Experiment 2) on N2pc onset latencies and mean amplitudes in constant-color versus variable-color blocks. For N2pc onset latencies,  $B_{01}$  values were 3.81 and 3.08 for Experiments 1 and 2, respectively, providing good evidence (Jeffreys, 1961) for the null hypotheses (that there was indeed no difference in the effects of color load on N2pc onsets between constant-color and variable-color blocks). For N2pc mean amplitudes,  $B_{01}$  values were 3.79 and 2.28 for Experiments 1 and 2, which again supports the null hypothesis.

2. An electrophysiological marker for target identification processes that is elicited after the allocation of spatial attention to candidate target objects is the sustained contralateral posterior negativity (SPCN component; Jolicœur, Brisson, & Robitaille, 2008; Mazza, Turatto, Umiltà, & Eimer, 2007). The SPCN typically emerges around 350 msec after target display onset and is assumed to be linked to the activation of target representations in visual working memory during the identification and categorization of target objects. In this study, SPCN components followed the N2pc to target objects at poststimulus latencies of around 350–700 msec (not shown in Figures). For Experiment 1, analyses of SPCN mean amplitudes showed that this component was larger during variable-color relative to constant-color blocks,  $F(1, 14) = 12.4, p = .003, \eta_p^2 = 0.47$ , in line with a more sustained activation of visual working memory during target identification in variable-color blocks. However, because no such SPCN amplitude differences between variable-color and constant-color blocks were found in Experiment 2,  $F(1, 14) < 1$ , this conclusion requires additional confirmation in future studies.

## REFERENCES

Barrett, D. J. K., & Zobay, O. (2014). Attentional control via parallel target-templates in dual-target search. *PLoS One*, *9*, 1–9.

- Beck, V. M., Hollingworth, A., & Luck, S. J. (2012). Simultaneous control of attention by multiple working memory representations. *Psychological Science*, *23*, 887–898.
- Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional templates in visual working memory. *Journal of Neuroscience*, *31*, 9315–9322.
- Christie, G. J., Livingstone, A. C., & McDonald, J. J. (2015). Searching for inefficiency in visual search. *Journal of Cognitive Neuroscience*, *27*, 46–56.
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87–114.
- Czerwinski, M., Lightfoot, N., & Shiffrin, R. M. (1992). Automatization and training in visual search. *American Journal of Psychology*, *105*, 271–315.
- Dombrowe, I., Donk, M., & Olivers, C. N. L. (2011). The costs of switching attentional sets. *Attention, Perception, & Psychophysics*, *73*, 2481–2488.
- Duncan, J., & Humphreys, G. (1992). Beyond the search surface: Visual search and attentional engagement. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 578–588.
- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*, 225–234.
- Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences*, *18*, 526–535.
- Eimer, M. (2015). EPS Mid-Career Award 2014: The control of attention in visual search—Cognitive and neural mechanisms. *Quarterly Journal of Experimental Psychology*, *68*, 2437–2463.
- Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, *24*, 193–198.
- Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*, *20*, 1423–1433.
- Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1030–1044.
- Grubert, A., & Eimer, M. (2013). Qualitative differences in the guidance of attention during single-colour and multiple-colour visual search: Behavioural and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 1433–1442.
- Grubert, A., & Eimer, M. (2015). Rapid parallel attentional target selection in single-color and multiple-color visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *41*, 86–101.
- Grubert, A., & Eimer, M. (2016). The speed of serial attention shifts in visual search: Evidence from the N2pc component. *Journal of Cognitive Neuroscience*, *28*, 319–332.
- Grubert, A., & Eimer, M. (in press). All set, indeed! N2pc components reveal simultaneous attentional control settings for multiple target colors. *Journal of Experimental Psychology: Human Perception and Performance*.
- Gunseli, E., Olivers, C. N., & Meeter, M. (2014). Effects of search difficulty on the selection, maintenance, and learning of attentional templates. *Journal of Cognitive Neuroscience*, *26*, 2042–2054.
- Hopf, J. M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., et al. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex*, *10*, 1233–1241.

- Houtkamp, R., & Roelfsema, P. R. (2009). Matching of visual input to only one item at any one time. *Psychological Research, 73*, 317–326.
- Irons, J. L., Folk, C. L., & Remington, R. W. (2012). All set! Evidence of simultaneous attentional control settings for multiple target colors. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 758–775.
- Ishihara, S. (1972). *Tests for color-blindness*. Tokyo: Kanehara Shuppan.
- Jeffreys, H. (1961). *Theory of probability* (3rd ed.). Oxford: Oxford University Press, Clarendon Press.
- Jolicœur, P., Brisson, B., & Robitaille, N. (2008). Dissociation of the N2pc and sustained posterior contralateral negativity in a choice response task. *Brain Research, 1215*, 160–172.
- Lien, M.-C., Ruthruff, E., Goodin, Z., & Remington, R. W. (2008). Contingent attentional capture by top-down control settings: Converging evidence from event-related potentials. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 509–530.
- Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95*, 492–527.
- Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 1000–1014.
- Mazza, V., Turatto, M., Umiltà, C., & Eimer, M. (2007). Attentional selection and identification of visual objects are reflected by distinct electrophysiological responses. *Experimental Brain Research, 181*, 531–536.
- Menneer, T., Cave, K. R., & Donnelly, N. (2009). The cost of search for multiple targets: Effects of practice and target similarity. *Journal of Experimental Psychology: Applied, 15*, 125–139.
- Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology, 35*, 99–115.
- Moore, K. S., & Weissman, D. H. (2010). Involuntary transfer of a top-down attentional set into the focus of attention: Evidence from a contingent attentional capture paradigm. *Attention, Perception, & Psychophysics, 72*, 1495–1502.
- Neisser, U., Novick, R., & Lazar, R. (1963). Searching for ten targets simultaneously. *Perceptual and Motor Skills, 17*, 955–961.
- Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences, 15*, 327–334.
- Reinhart, R., Carlisle, N. B., & Woodman, G. F. (2014). Visual working memory gives up attentional control early in learning: Ruling out interhemispheric cancellation. *Psychophysiology, 51*, 800–804.
- Reinhart, R., & Woodman, G. F. (2014). High stakes trigger the use of multiple memories to enhance the control of attention. *Cerebral Cortex, 24*, 2022–2035.
- Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian *t*-tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review, 16*, 225–237.
- Schneider, W., & Shiffrin, R. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review, 84*, 1–66.
- Shiffrin, R., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review, 84*, 127–190.
- Stroud, M. J., Menneer, T., Cave, K. R., Donnelly, N., & Rayner, K. (2011). Search for multiple targets of different colours: Misguided eye movements reveal a reduction of colour selectivity. *Applied Cognitive Psychology, 25*, 971–982.
- Ulrich, R., & Miller, J. O. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology, 38*, 816–827.
- Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature, 428*, 748–751.
- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 92–114.
- Wolfe, J. M. (2007). Guided Search 4.0: Current progress with a model of visual search. In W. Gray (Ed.), *Integrated models of cognitive systems* (pp. 99–119). New York: Oxford University Press.
- Wolfe, J. M., Yu, K. P., Stewart, M. I., Shorter, A. D., Friedman-Hill, S. R., & Cave, K. R. (1990). Limitations on the parallel guidance of visual search: Color × color and orientation × orientation conjunctions. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 879–892.
- Woodman, G. F., Carlisle, N. B., & Reinhart, R. M. G. (2013). Where do we store the memory representations that guide attention? *Journal of Vision, 13*, 1.
- Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature, 400*, 867–886.