

Rapid Parallel Attentional Target Selection in Single-Color and Multiple-Color Visual Search

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Previous work has demonstrated that when targets are defined by a constant feature, attention can be directed rapidly and in parallel to sequentially presented target objects at different locations. We assessed how fast attention is allocated to multiple objects when this process cannot be controlled by a unique color-specific attentional template. N2pc components were measured as temporal markers of the attentional selection of 2 color-defined targets that were presented in rapid succession. Both targets either had the same color (one color task) or differed in color (two color task). Although there were small but systematic delays of target selection in the two color task relative to the one color task, attention was allocated extremely rapidly to both target objects in the two color task, which is inconsistent with the hypothesis that their selection was based on a slow switch between different color templates. Two follow-up experiments demonstrated that these delays did not reflect template switch costs, but were the result of competitive interactions between simultaneously active attentional templates. These results show that the control of focal attention during multiple-feature search operates much faster and more flexibly than is usually assumed.

Keywords: visual attention, top-down control, visual search, event-related brain potentials, parallel selection

In complex real-life visual scenes, where multiple objects compete for access to visual perception and action control, selective attention determines which of these objects are processed preferentially at any given moment in time. When observers search for a particular target object, the allocation of attention is guided by representations of target-defining features (attentional templates or top-down attentional sets) in working memory (e.g., Duncan & Humphreys, 1989; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Wolfe & Horowitz, 2004). Attentional templates can be set up prior to the arrival of visual search displays, and facilitate the visual processing of template-matching visual objects in a spatially selective fashion (e.g., Desimone & Duncan, 1995; Eimer, 2014). In situations where multiple potentially task-relevant objects appear simultaneously or in rapid succession, template-guided selection processes should be able to allocate attention flexibly and rapidly in line with current task demands. This is required when observers search for several target objects or features at the same time, or when they encounter a new object that requires immediate attention while their attention is already focused elsewhere.

The question whether attention can be allocated simultaneously to several objects at different locations in the visual field is still under dispute. According to serial models of visual search (e.g., Treisman & Gelade, 1980; Wolfe, 1994, 2007), focal attention is always directed to one object at a time, and the selection of multiple objects requires sequential movements of the attentional focus. Parallel models of visual selectivity (e.g., Desimone & Duncan, 1995) assume that attention can be simultaneously allocated to several objects in a visual scene. A similar multifocus account of visual attention has been proposed to account for the ability to simultaneously track multiple moving objects in the visual field (Cavanagh & Alvarez, 2005). In a recent study from our lab (Eimer & Grubert, 2014b), we employed event-related potential (ERP) markers of attentional object selection to demonstrate that focal attention can be allocated in parallel and independently to different target objects. In this study, two search arrays that each contained a color-defined target and a distractor object in a different color on opposite sides were presented in rapid succession. The two target items always had the same color, and the stimulus onset asynchrony (SOA) separating the two displays was either 10 ms or 100 ms. Participants' task was to report on each trial whether the two target-color items in the two displays belonged to the same alphanumeric category (two letters, two digits) or not (one letter and one digit). To track the attentional selection of the two sequentially presented target-color objects in real time, we measured N2pc components triggered by these objects. The N2pc is an enhanced negativity that is elicited at posterior electrodes contralateral to the visual field of a target object in multistimulus visual displays. This component that typically emerges 180 to 200 ms after stimulus onset, is generated in extrastriate areas of the ventral visual processing stream (Hopf et al., 2000), and reflects the attentional selection of candidate target

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objects among distractors in visual search (e.g., Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999). Because the N2pc is computed by comparing contralateral and ipsilateral ERP waveforms to targets in the left versus right visual field, no N2pc is elicited for target objects that appear on the vertical meridian (Eimer & Grubert, 2014b; Eimer, Kiss, & Nicholas, 2011; Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, & Theeuwes, 2006; Woodman & Luck, 1999). In our previous study (Eimer & Grubert, 2014b), the target/nontarget pair in one display always appeared on the horizontal meridian (to the left and right of fixation), and the stimulus pair in the other display was presented on the vertical meridian (above and below fixation; see Figure 1). Trials where the horizontal display preceded the vertical display (horizontal target first: H1 targets) and trials where this order was reversed (horizontal target second: H2 targets) were randomly intermixed. This procedure allowed us to measure the attentional selection of horizontal target objects, as reflected by the N2pc component, independently of any parallel attentional processing of the vertical target objects in the other display on the same trial. When both displays were separated by a 100-ms SOA, the N2pc to H1 targets preceded the N2pc to H2 targets by almost exactly 100 ms. Critically, when the SOA between the two displays was reduced to 10 ms, the latency difference of the N2pc components to the two targets again mirrored this objective time interval precisely, as the N2pc to H2 targets emerged 10 ms later than the N2pc to H1 targets. Furthermore, both N2pc components were equal in size and overlapped in time. These observations demonstrate that focal attention can be allocated rapidly and in parallel to several target objects, with each selection process following its own independent time course.

Although these findings provide new electrophysiological evidence in favor of parallel models of attentional object selection,

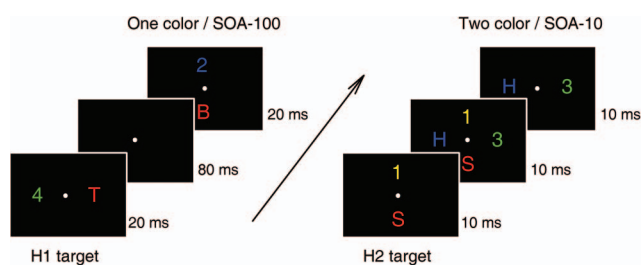


Figure 1. Schematic illustration of the time course of stimulus events in Experiment 1. On each trial, two displays with a color-defined target and a nontarget-color distractor on opposite sides were presented sequentially. One target/nontarget pair appeared on the horizontal meridian and the other on the vertical meridian, and the stimulus onset asynchrony (SOA) between the two displays was 100 ms or 10 ms (in different blocks). In the one color task, all targets had the same color. In the two color task, there were two possible target colors, and target color always changed between the first and second display. Participants had to judge the alphanumeric category of the two target objects (same/different). Left: A trial from the one color task. The two targets are red and separated by an SOA of 100 ms. The first target appears on the horizontal meridian (H1 target), and the second target is presented on the vertical meridian. Right: A trial from the two color task. The two targets are yellow and blue, the SOA between the two displays is 10 ms. The first target appears on the vertical meridian, while the second target is presented on the horizontal meridian (H2 target). See the online article for the color version of this figure.

and against the hypothesis that focal attention is always allocated in a strictly sequential fashion to different objects, this may only apply to situations where multiple target objects are defined by a shared perceptual feature, and their selection can therefore be guided by a single attentional template. In our earlier study, target items always had the same color (e.g., all targets were red), and participants could therefore maintain a single color-specific attentional set throughout the experiment. It is well-known that in such contexts, objects with target-matching features will capture attention in a task-set dependent fashion, even when they are known to be task irrelevant (e.g., Eimer & Kiss, 2008; Folk, Remington, & Johnston, 1992). The rapid parallel allocation of attention to different target objects observed in our previous study (Eimer & Grubert, 2014b) may therefore be specific to conditions that elicit task-set contingent involuntary attentional capture, and may not be observed in task contexts where target-defining features are no longer fixed. The aim of the present study was to measure the allocation of spatial attention to sequentially presented color-defined target objects that could have one of two possible colors, and to compare it to the attentional selection of two successive target objects in a task where a single-color attentional template can be applied. Experimental procedures were similar to Eimer and Grubert (2014b), except that target definitions differed between task conditions. The one color task was identical to our previous study. Participants had to select two target items in two successive displays, and to report whether their alphanumeric identity was the same or different. Targets were defined by one constant color throughout this task condition. In the new two color task, instructions were the same, except that two different colors were now designated as possible target colors for each participant. In Experiment 1, the target item in the first display was presented randomly and unpredictably in one of these colors, and the target in the second array always had the other color (see Figure 1). Target-color items were accompanied by a nontarget-color distractor on the opposite side in both tasks. Horizontal target/nontarget displays preceded vertical displays on half of all trials (H1 targets), and this order was reversed in the other half (H2 targets; see Figure 1). In different blocks, the SOA separating the first and second display was 100 ms or 10 ms.

The N2pc results for the one color task should confirm the findings from our earlier study (Eimer & Grubert, 2014b). The onset of N2pc components to H1 and H2 targets should closely match the objective onset delay between the two displays. For the SOA-10 condition, the two N2pc components to H1 and H2 targets should be identical in amplitude and overlap in time, demonstrating that when the selection of two successively presented target items can be guided by a single attentional template for one particular target color, attention can be allocated rapidly and in parallel to both target objects, with each selection process following its own independent time course. The critical question concerned the time course of attentional object selection in the new two color task. In this task, attention could no longer be guided by a unique color-specific attentional template, and this should affect the speed and efficiency with which attention was allocated to target objects in the first and second display.

Previous research has demonstrated severe limitations in observers' ability to simultaneously maintain multiple object- or feature-specific attentional templates. For example, Houtkamp and Roelfsema (2009) found impaired target detection performance in

a rapid serial visual presentation (RSVP) stream when observers searched for two possible target objects or features relative to search for a single target. Modeling of these results suggested that exactly one attentional template can be active at a time (see also [Olivers et al., 2011](#)). Further evidence for the costs associated with searching simultaneously for multiple targets was obtained by [Stroud, Menneer, Cave, Donnelly, and Rayner \(2011\)](#) in visual search tasks that simulated airport security checking procedures. Search for a single object or for two different objects that were defined by the same color was much faster and more efficient than search for two different objects in different colors. During multiple-feature search, distractor objects with nontarget colors were fixated more often than during single-feature search (see also [Menneer, Cave, & Donnelly, 2009](#), for similar observations). Impaired target selection during multiple-feature search also was demonstrated in a recent ERP study ([Grubert & Eimer, 2013](#)). In this experiment, participants searched for color-defined target digits that were accompanied by a single gray distractor object in the opposite visual field. In one task condition, target color was constant. In another condition, targets could have one of two equally likely colors. Response times (RTs) were slower and N2pc components were delayed during multiple-color search relative to single-color search, demonstrating less efficient attentional target selection under conditions where it could not be guided by a unique feature-specific attentional template. Furthermore, items in a nontarget-color that were presented together with a gray distractor item on half of all trials captured attention and gained access to visual working memory during multiple-color search, but were excluded from attentional processing during single-color search, indicating that top-down attentional control settings could be applied more effectively and selectively when targets were defined by one particular constant feature. If this is the case, task performance should generally be much better in the one color task than in the two color task of the present study. In particular, impairments in the control of attentional target selection in the two color task should be reflected by delayed N2pc components to successively presented target objects in this task relative to the one color task.

In addition to generic processing costs associated with multiple-color search, target selection in the two color task of Experiment 1 may be additionally impaired by the fact that there was always a color change between the first and second target in each trial. If attentional object selection is controlled by feature-specific attentional templates, and only one template can be active at any point in time ([Houtkamp & Roelfsema, 2009](#)), participants will have to rapidly switch color templates in this task to select target objects in the second display. Previous research has suggested that switching between attentional templates is a time-consuming process. In a study by [Wolfe, Horowitz, Kenner, Hyle, and Vasan \(2004\)](#), observers searched for different target objects on successive trials, and target identity was specified by picture or word cues that were presented at different SOAs before each search display. Target detection was delayed with short SOAs, indicating that new attentional templates cannot be activated instantaneously (see also [Vickery, King, & Jiang, 2005](#), for analogous observations). Along similar lines, [Dombrowe, Donk, and Olivers \(2011\)](#) asked observers to execute sequential eye movements to two color-defined targets in the left and right visual field, and found performance costs when these two targets differed in color relative to a single-

color condition. It is interesting that the fastest eye movements toward the side of the second target were often directed toward distractor objects that matched the color of the first target. [Dombrowe et al. \(2011\)](#) suggested that it may take 250 to 300 ms to switch between different color templates. The Boolean map theory of visual attention ([Huang & Pashler, 2007](#)) also predicts impaired attentional object selection in tasks that require a rapid switch between feature-specific attentional templates. According to this theory, visual scenes are partitioned into selected and nonselected regions before selected information is consciously accessed. Selection operates through the creation of Boolean maps that specify selected and nonselected areas of visual space on the basis of one particular feature value from one dimension (e.g., all red items in a display). More important, the successive attentional selection of targets with different features in the same dimension (e.g., the selection of a red target followed by the selection of a green target) requires the time-consuming sequential creation of two independent Boolean maps.

If switching between feature-specific attentional templates is an effortful process that takes several hundred milliseconds to complete (e.g., [Dombrowe et al., 2011](#)), the allocation of attention to the second target should be strongly delayed in the two color task of Experiment 1, in particular when the onset asynchrony between the two search displays is extremely short (10 ms). This should be reflected in marked performance decrements relative to the one color task, and in large delays of N2pc components to H2 targets. On the other hand, it is possible that two color-specific templates can be active simultaneously. In this case, there should only be moderate performance and N2pc differences between the one and two color tasks of Experiment 1. In Experiments 2 and 3, different versions of the two color task were employed to investigate how these differences are affected when the order of the two target-color items in the first and second display is constant and therefore fully predictable or completely unpredictable.

Experiment 1

Method

Participants. Fourteen participants were paid to take part in this study. Two of them were excluded from analysis due to excessive eye movement activity. The remaining 12 participants were aged between 26 and 40 years (M age 33 years; $SD = 5.1$ years). Seven were women, and three were left-handed. They all had normal or corrected-to-normal vision and normal color vision, as substantiated by means of the Ishihara color vision test ([Ishihara, 1972](#)).

Stimuli and procedure. Stimuli were presented on a 22-inch Samsung wide SyncMaster 2233 LCD monitor (resolution of $1,280 \times 1,024$ pixels, 100 Hz refresh rate; 16-ms black-to-white-to-black response time, as verified with a photodiode). Participants were seated in a dimly illuminated cabin and viewed the screen at a distance of approximately 100 cm. Stimulus presentation, timing, and response recollection were controlled by an LG Pentium PC running under Windows XP, using the Cogent 2000 toolbox (Wellcome Department of Imaging Neuroscience, London, UK; www.vislab.ucl.ac.uk/Cogent/) for MATLAB (MathWorks, Inc.).

Stimuli were colored uppercase letters ("B," "H," "S," or "T") or digits ("1," "2," "3," or "4"), subtending 0.9×0.9 degrees of

visual angle. They were presented at an eccentricity of 2.4° from central fixation against a black background. The four possible object colors were red (CIE color coordinates: .637/.329), green (.264/.556), blue (.179/.168), and yellow (.423/.461). All colors were equiluminant (~ 7.5 cd/m²). A central gray fixation point (.321/.352; 0.2° × 0.2° of visual angle) remained continuously present throughout each experimental block. On each trial, two successive stimulus displays were presented for 20 ms. Each stimulus display contained one object in a target color and another distractor object in a randomly selected nontarget color (see Figure 1). Four different stimulus identities were selected randomly for each trial. On each trial, one target–nontarget pair was presented on the horizontal meridian (left and right of fixation), and the other pair appeared on the vertical meridian (above and below fixation). In half of all trials, the horizontal stimulus pair was presented first (horizontal target first: H1 trials). In the other half, the vertical target/nontarget display preceded the horizontal display (horizontal target second: H2 trials). H1 and H2 trials were randomly intermixed in each block, and the position of the target in these two displays (left/right; top/bottom) was randomly and independently determined on each trial. Participants' task was to report whether the alphanumeric identity of the two successively presented color-defined target items was the same (two digits or two letters) or different (one digit, one letter) by pressing one of two purpose-built vertically aligned response keys. Half of all participants pressed the top key with their left hand and the bottom key with their right hand, and this hand-to-key mapping was reversed for the other half. The mapping between response ("same" vs. "different") and key was counterbalanced across participants. Trials requiring a "same" or "different" response were equiprobable and randomly intermixed in each block.

There were two blocked task conditions. In the one color task, all targets were defined by the same color (e.g., participants had to match the two successive red items on all trials). Target color was counterbalanced across participants, so that each of the four colors served as target color for three participants. The other three colors served as nontarget colors in this task. In the two color task, there were two possible target colors. On each trial, the target item in one of the two successively presented displays appeared in one of these colors and the item in the other display was presented in the other color. The order in which these two target colors appeared was randomly determined for each trial. For half of all participants, target colors were red and green, and nontarget colors yellow and blue. 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 nontarget colors. For each participant, the target color for the one color task served as nontarget color in the two color task (e.g., a participant who searched for red targets in the one color task would search for yellow and blue targets in the two color task). In both tasks, the combination of target and nontarget colors in the two subsequent displays was determined randomly on each trial, with the restriction that nontarget colors were never repeated within one trial.

For each task, two blocked SOA conditions were run (see Figure 1). In SOA–100 blocks, the two consecutive stimulus displays were separated by an 80-ms blank interval. In SOA–10 blocks, the onset of the first display preceded the onset of the second display by only 10 ms (i.e., there was a 10-ms overlap between these two displays). In all blocks, the interval between the offset of the

second display and the onset of the first display on the next trial was 1,900 ms.

The experiment contained 24 blocks, with 64 trials per block. There were 16 trials for each combination of target location (left, right, top, or bottom) and display sequence (H1 or H2). The one color and two color tasks were each run in 12 successive blocks (with six successive blocks for the SOA–100 and SOA–10 conditions). Six participants started the experiment with the one color task, and the other half with the two color task. Within each task, six participants started with the SOA–10 condition, and the other six with the SOA–100 condition. Those participants who had started the first task with the SOA–10 condition started their second task with the SOA–100 condition, and vice versa. One practice block preceded the experimental blocks for both tasks.

EEG recording and data analyses. The continuous EEG was DC-recorded from 23 scalp electrodes (Fpz, F7, F3, Fz, F4, F8, FC5, FC6, T7, C3, Cz, C4, T8, CP5, CP6, P7, P3, Pz, P4, P8, PO7, PO8, Oz), sampled at a rate of 500 Hz, and digitally low-pass filtered at 40 Hz. No other off-line filters were applied. All channels were online referenced to the left earlobe and rereferenced off-line to the average of both earlobes. Trials contaminated with artifacts (eye movements exceeding ± 30 μV in the HEOG channels; eyeblinks exceeding ± 60 μV at Fpz; muscular movements exceeding ± 80 μV in all other channels), and trials with incorrect, anticipatory (faster than 200 ms), very slow (slower than 1,500 ms), or missing responses were excluded from EEG analyses. This led to a rejection of 5.6% and 4.9% of all trials in the SOA–10 and SOA–100 conditions of the one color task, and of 5.3% and 4.6% of all trials in the SOA–10 and SOA–100 conditions of the two color task. For the remaining trials, EEG was segmented into epochs ranging from 100 ms prior to 500 ms after the onset of the first stimulus display, and was baseline corrected relative to the 100 ms prestimulus interval. EEG was averaged separately for each of the 16 combinations of task (one color and two color), SOA (100 ms and 10 ms), display sequence (H1 trials and H2 trials), and horizontal target location (left and right).

N2pc components were quantified on the basis of ERP waveforms measured at lateral posterior electrodes PO7 and PO8. N2pc onset latencies were measured on the basis of difference waveforms, computed by subtracting ERPs at PO7/8 ipsilateral to the target side from contralateral ERPs. Onset latencies were determined with a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998). Twelve grand-average difference waves were computed for each experimental condition, each excluding one different participant from the original sample. N2pc onset latency was defined as the point in time when each subsample difference wave reached an absolute onset criterion of $-1 \mu\text{V}$.¹ Differences in N2pc onset latencies between experimental conditions were assessed with repeated-measures analyses of variances (ANOVAs)

¹ A fixed onset criterion of $-1 \mu\text{V}$ was chosen to avoid a distortion of N2pc onset latency estimates by N2pc amplitude differences between experimental conditions (see Grubert, Krummenacher, & Eimer, 2011, for the same procedure). The N2pc onset latency analyses reported in this article also were run with a relative onset criterion of 50% (where N2pc onset latency is defined as the point in time when 50% of the peak amplitude is reached in each subsample difference wave), as described by Miller et al. (1998). The results of these analyses confirmed those obtained with the fixed onset criterion.

and two-tailed t tests, with F and t values corrected according to the formulas described by Ulrich and Miller (2001) and Miller et al. (1998). The corrected tests are indicated with F_c and t_c , respectively. Because N2pc components emerged at different poststimulus latencies in different experimental conditions, the time intervals used for measuring N2pc mean amplitudes were determined separately for each condition on the basis of the grand-averaged N2pc peak latency for this condition. N2pc mean amplitudes were measured for an 80-ms interval centered on this peak latency (from 40 ms before to 40 ms after the N2pc peak for a particular experimental condition). The resulting N2pc mean amplitude windows for H1 trials were 204 to 284 ms (one color/SOA-10), 195 to 275 ms (one color/SOA-100), 205 to 285 ms (two color/SOA-10), and 194 to 274 ms (two color/SOA-100). For H2 trials, the respective time windows were 210 to 290 ms (one color/SOA-10), 315 to 395 ms (one color/SOA-100), 224 to 304 ms (two color/SOA-10), and 329 to 409 ms (two color/SOA-100).

Results

Behavioral performance. Anticipatory or exceedingly slow responses (RTs faster than 200 ms or slower than 1,500 ms) were removed from analysis, resulting in the exclusion of less than 0.5% of all trials. Table 1 shows RTs and error rates for the different tasks and SOA conditions of Experiment 1. A repeated-measures ANOVA on correct RTs with the factors task (one color vs. two color task) and SOA (SOA-100 vs. SOA-10) showed that RTs were considerably faster in the one color task than in the two color task (606 ms vs. 745 ms), $F(1, 11) = 50.4$, $p < .001$. There was no main effect of SOA, $F(1, 11) = 1.5$, $p = .249$, and no interaction between task and SOA, $F(1, 11) = 2.3$, $p = .161$. To investigate RT differences between “same” responses on trials where the alphanumeric categories of the two target items matched and “different” responses on category-mismatch trials, an additional analysis of correct RTs was conducted for the factors target category (same vs. different) and task (one color vs. two color). RTs were faster on category-match versus category-mismatch trials (651 ms vs. 700 ms), resulting in a main effect of target category, $F(1, 11) = 42.6$, $p < .001$ (see Table 1). An

interaction between target category and task, $F(1, 11) = 17.8$, $p = .001$, reflected the fact that this RT advantage for category match as compared to mismatch trials was more pronounced in the two color task than in the one color task (60 ms vs. 38 ms).

Although error rates tended to be higher in the two color task relative to the one color task (5.0% vs. 3.0%), this difference only approached significance, $F(1, 11) = 4.6$, $p = .054$. There was also a tendency for more errors with long relative to short SOAs (4.7% vs. 3.3%), but this difference was also not statistically reliable, $F(1, 11) = 4.0$, $p = .069$, nor was the interaction between task and SOA, $F(1, 11) = 1.7$, $p = .223$.

N2pc components.

One color task. Figure 2 (left and middle panels) shows ERPs at posterior electrodes PO7/8 contralateral and ipsilateral to the side of the horizontal target-color item for trials where this item appeared in the first display (H1) or in the second display (H2). ERPs are shown separately for the SOA-100 and the SOA-10 conditions. In both SOA conditions, N2pc components were elicited to H1 and H2 targets. This was substantiated by repeated-measures ANOVAs with the factors display sequence (H1 vs. H2 trials) and laterality (electrode ipsilateral vs. contralateral to the side of the horizontal target) conducted separately for the SOA-100 and SOA-10 conditions. Both ANOVAs revealed a main effect of laterality, $F_s(1, 11) > 17.1$, $p_s < .003$, confirming that N2pc components were reliably elicited by horizontal target items. More important, there was no interaction between laterality and display sequence for either SOA condition, $F_s(1, 11) < 1$, demonstrating that N2pc amplitudes were statistically equivalent on H1 and H2 trials, both when the two targets were separated by a 100-ms or by a 10-ms SOA.

The right panel of Figure 2 shows N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for trials where the horizontal target-color item appeared in the first or second display, and for both SOA conditions. In blocks where both displays were separated by a 100-ms SOA, N2pc components to H1 and H2 targets showed no temporal overlap. Their onset latency difference was 110 ms (202 ms vs. 312 ms), $t_c(11) = 20.8$, $p < .001$, which closely matched the physical onset

Table 1
RTs and Error Rates, Shown Separately for All Task Conditions of Experiments 1 to 3

Task condition	SOA	RTs overall	RTs same response	RTs different response	Error rates
Experiment 1					
One color	100	606 (80)	587 (83)	625 (81)	3.5 (4.0)
	10	606 (57)	587 (53)	625 (62)	2.6 (1.9)
Two color	100	729 (101)	699 (101)	759 (104)	6.0 (5.2)
	10	761 (113)	731 (109)	791 (119)	4.0 (4.9)
Experiment 2					
One color	100	575 (64)	563 (66)	587 (64)	3.6 (3.7)
Two color variable	100	680 (100)	664 (97)	695 (105)	4.9 (3.6)
Two color fixed	100	679 (108)	657 (103)	700 (114)	4.4 (3.0)
Experiment 3					
Two color variable	100	699 (78)	665 (69)	734 (91)	7.6 (7.1)
Two color random/color repetition	100	635 (75)	605 (73)	666 (83)	5.9 (6.0)
Two color random/color change	100	708 (82)	678 (79)	739 (92)	7.9 (9.2)

Note. Reaction times (RTs) given in milliseconds. Error rates given in percentages. SOA = stimulus onset asynchrony.

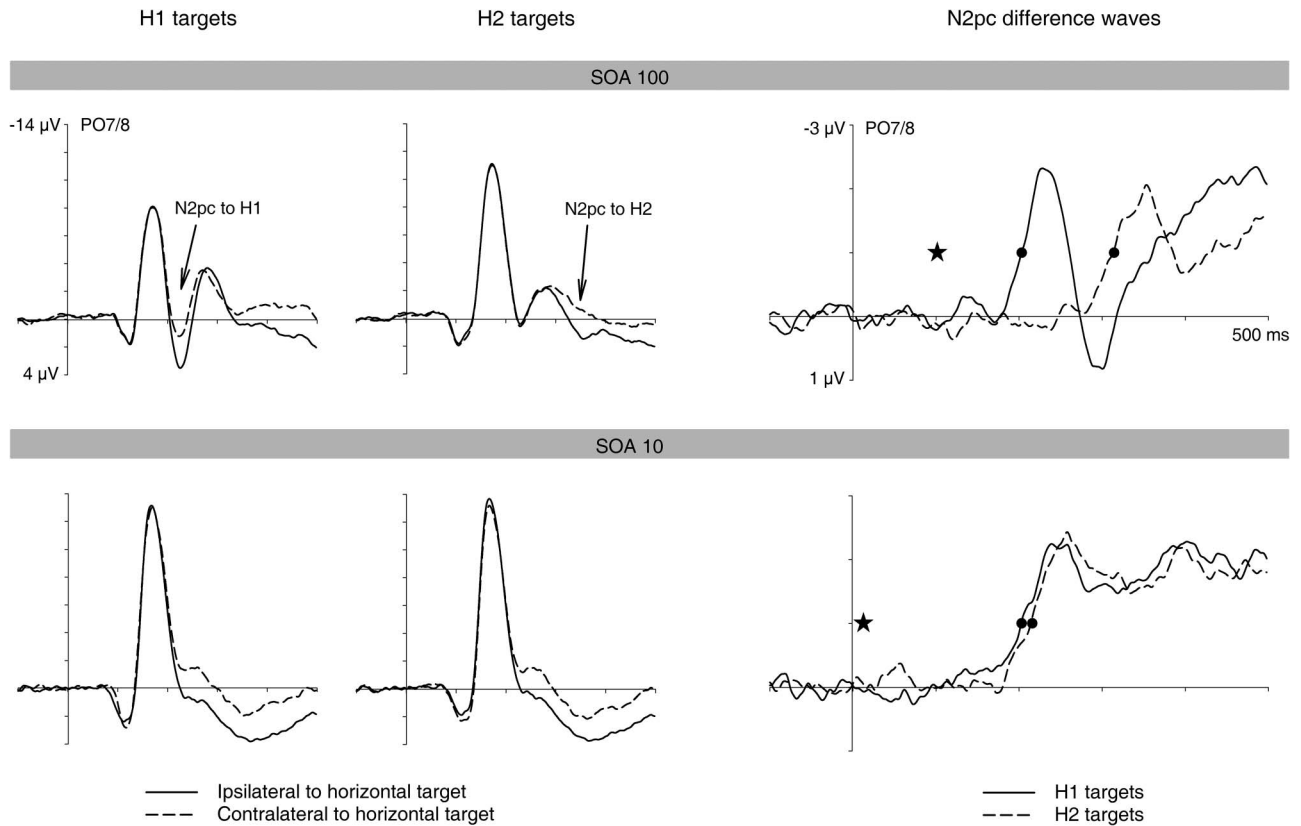


Figure 2. N2pc results obtained in the one color task in the SOA-100 condition (top panel) and the SOA-10 condition (bottom panel) of Experiment 1. Grand-average event-related potential (ERP) waveforms measured in the 500-ms interval after the onset of the first display at posterior electrodes PO7/PO8 contralateral and ipsilateral to the target in the first display are shown separately for trials with a horizontal target in the first display (H1 targets) or in the second display (H2 targets). The panels on the right show N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for H1 and H2 targets. Stars mark the onset of the second display (100 or 10 ms after the onset of the first display). Circles mark the points in time when N2pc amplitudes reach the onset criterion value ($-1 \mu\text{V}$). The onset latency difference between N2pc components to H1 and H2 targets closely matches the objective time interval between the two target displays. SOA = stimulus onset asynchrony.

difference between the first and second display. When the SOA between both displays was 10 ms, N2pc components to H1 and H2 targets overlapped in time, but the onset of the N2pc to H2 targets was delayed by 11 ms relative to the onset of the N2pc to H1 targets (202 ms vs. 213 ms). This N2pc onset latency difference was statistically reliable, $t_c(11) = 2.7, p = .019$.

Two color task. Figure 3 shows ERP waveforms for the two color task. ERPs at contralateral and ipsilateral posterior electrodes (PO7/8) for the SOA-100 and SOA-10 conditions are displayed separately for trials where the horizontal target item appeared in the first or second display (H1 and H2 trials), together with the corresponding contralateral-ipsilateral difference waveforms. Overall, the pattern of N2pc results obtained in the two color task was similar to the one color task. Repeated-measures ANOVAs on N2pc mean amplitudes conducted separately for both SOA conditions with the factors display sequence and laterality obtained a main effect of laterality, $F_s(1, 11) > 32.3, ps < .001$, reflecting the presence of N2pc components to horizontal target items in the SOA-100 and SOA-10 conditions. As in the one color task, there

was no interaction between laterality and display sequence for either SOA condition, $F_s(1, 11) < 2.7, ps > .137$, indicating that N2pc components were equal in size on H1 and H2 trials.

The N2pc difference waveforms in Figure 3 (right panel) show the onset delay of the N2pc on H2 trials relative to H1 trials, separately for the SOA-100 and SOA-10 conditions. As in the one color task, the two N2pc components showed no temporal overlap when the SOA between the two displays was 100 ms, and considerable overlap with an SOA of 10 ms. In the SOA-100 condition, N2pc components emerged at a poststimulus latency of 213 ms and 338 ms on H1 and H2 trials, and this onset latency difference of 125 ms was highly significant, $t_c(11) = 31.5, p < .001$. In the SOA-10 condition, the N2pc on H2 trials was delayed by 31 ms relative to the N2pc on H1 trials (243 ms vs. 212 ms), and this difference was also reliable, $t_c(11) = 2.3, p = .045$.

Comparison of N2pc components between the one color and two color tasks. Although the overall temporal pattern of N2pc components on H1 and H2 trials was similar in both tasks, there were also some small but important differences. A comparison of

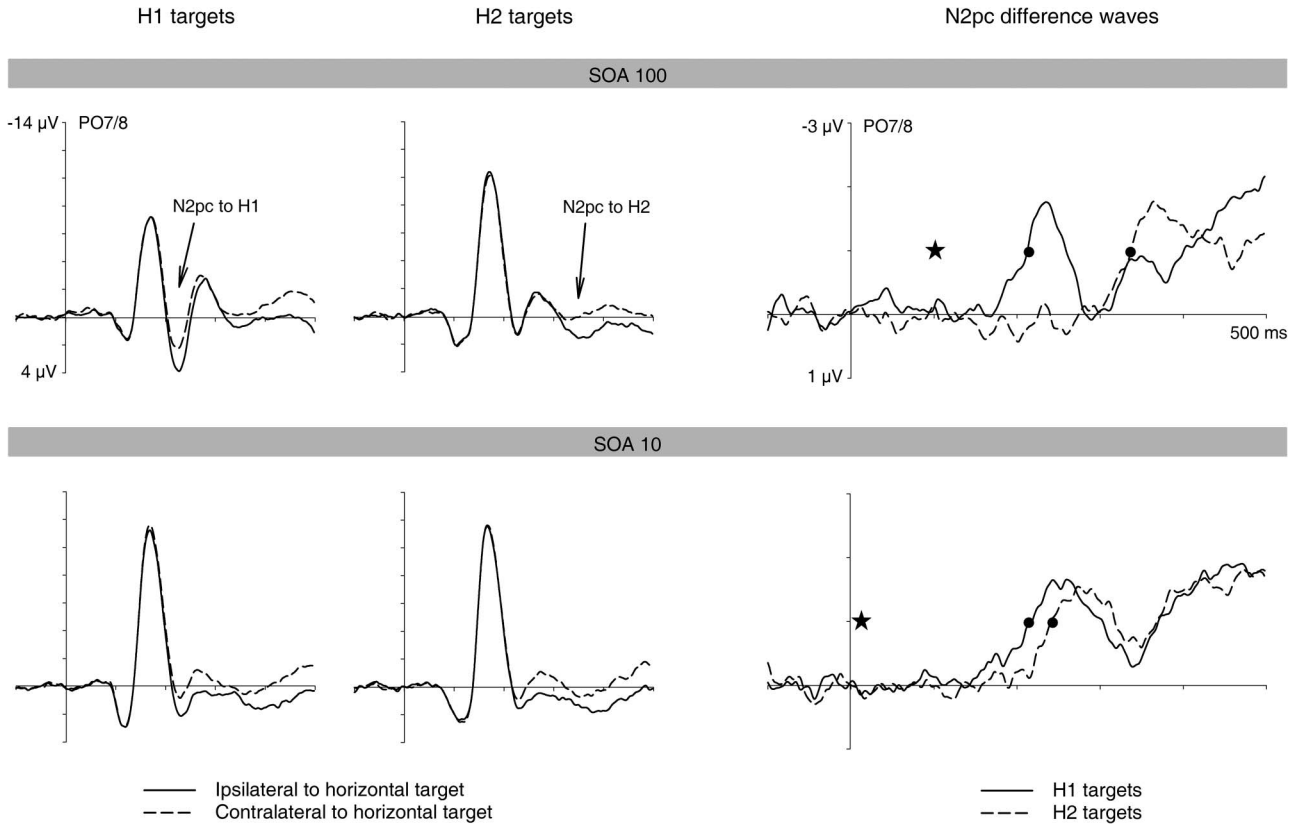


Figure 3. N2pc results obtained in the two color task in the SOA-100 condition (top panel) and the SOA-10 condition (bottom panel) of Experiment 1. Grand-average event-related potential (ERP) waveforms at electrodes PO7/PO8 contralateral and ipsilateral to the target in the first display are shown for trials with H1 and H2 targets, together with N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. Stars indicate the onset of the second display (100 or 10 ms after the onset of the first display), and circles the points when N2pc amplitudes reached the onset criterion value. Target N2pc component latencies again closely matched the objective onset latency between the two target displays. SOA = stimulus onset asynchrony.

the N2pc difference waveforms shown in Figures 2 and 3 suggests that the N2pc to horizontal targets in the first display emerged slightly later in the two color task relative to the one color task. Furthermore, there may have been an additional delay for the N2pc to horizontal targets in the second display in the two color task. These N2pc onset latency differences between the two tasks can be seen most clearly in Figure 4, which shows N2pc difference waveforms obtained in the one color and two color tasks for H1 and H2 trials in the SOA-100 and SOA-10 conditions. When the horizontal target appeared in the first display (H1 trials), the target N2pc emerged approximately 10 ms later in the two color task relative to the one color task (212 ms vs. 202 ms and 213 ms vs. 202 ms in the SOA-10 and SOA-100 conditions, respectively). A repeated-measures ANOVA of N2pc onset latency estimates in H1 trials with the factors task (one color vs. two color task) and SOA condition (100 vs. 10) obtained a main effect of task, $F_c(1, 11) = 14.6, p = .003$, confirming that the small N2pc onset delay for the two color task relative to the one color task was reliable. There was no Task \times SOA condition interaction, $F_c(1, 11) < 1$. When the horizontal target appeared in the second display (H2 trials), the N2pc to these targets was delayed by approximately 30 ms in the two color task relative to the one color task (243 ms vs. 213 ms and 338

ms vs. 312 ms in the SOA-10 and SOA-100 conditions, respectively). An ANOVA of N2pc onset latency estimates in H2 trials with the factors task and SOA condition obtained a main effect of task, $F_c(1, 11) = 17.7, p = .001$, confirming that the N2pc on H2 trials emerged reliably later in the two color task relative to the one color task. There was no Task \times SOA condition interaction, $F_c(1, 11) < 1$.

Because N2pc onset latencies were more strongly delayed in the two color task relative to the one color task for horizontal targets in the second display than for H1 targets, N2pc onset latency differences between H1 and H2 trials were therefore larger in the two color task (125 ms vs. 110 ms for the SOA-100 condition, 31 ms vs. 11 ms for the SOA-10 condition). An ANOVA on jackknife-derived N2pc latency differences between H1 and H2 trials (obtained by subtracting N2pc onset latencies on H1 trials from onset latencies on H2 trials) with the factors task (one color vs. two color task) and SOA (100 vs. 10) obtained an effect of SOA, $F_c(1, 11) = 90.0, p < .001$, and, more important, a main effect of task, $F_c(1, 11) = 8.0, p = .016$, thus confirming that the interval between the onset of the N2pc on H1 and H2 trials was reliably increased in the two color task than the one color task. There was no significant Task \times SOA interaction, $F_c(1, 11) < 1$,

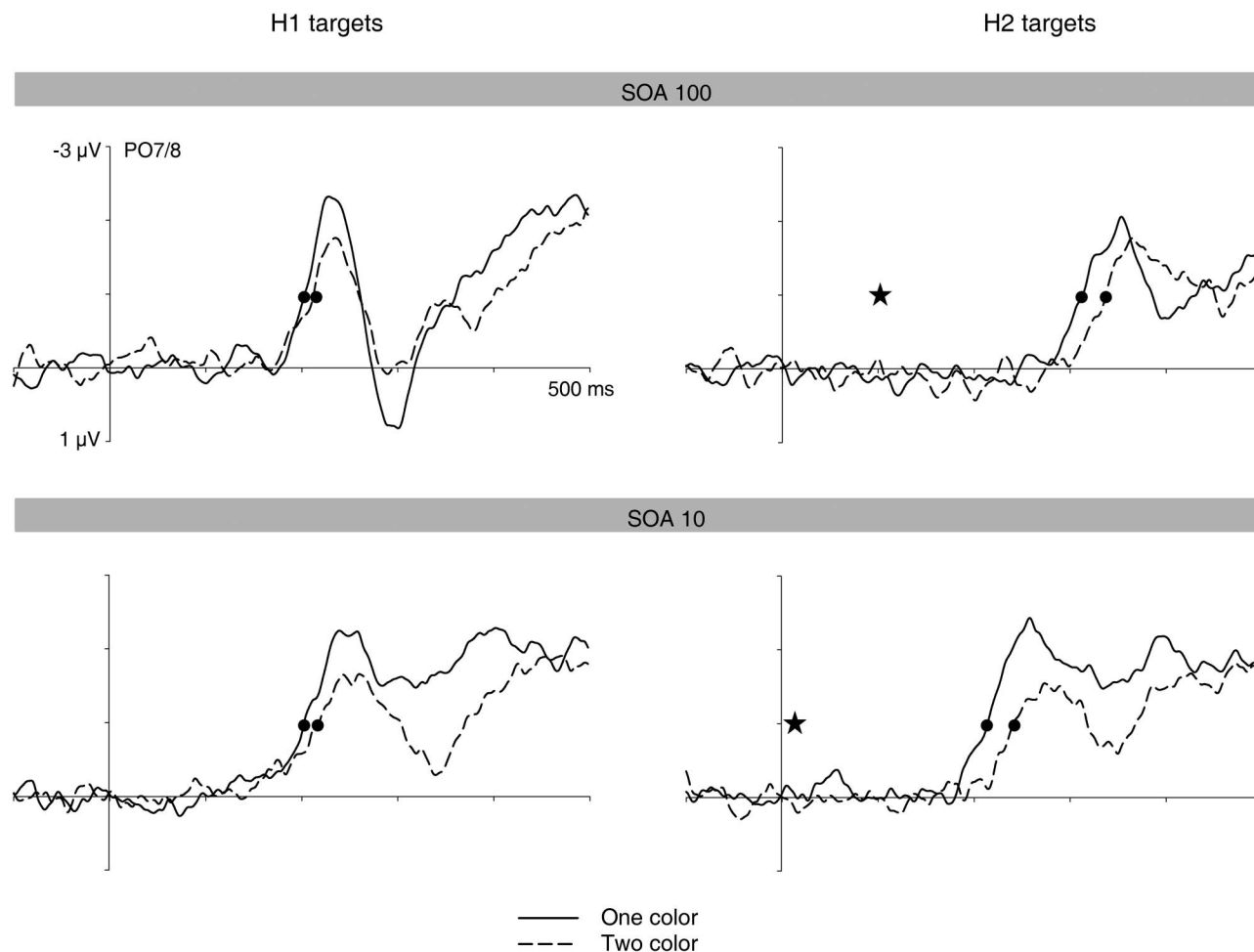


Figure 4. Comparison of target N2pc components obtained in response to H1 targets (left panels) and H2 targets (right panels) in the one and two color tasks of Experiment 1. N2pc difference waves obtained by subtracting ipsilateral from contralateral event-related potentials (ERPs) are shown separately for the SOA-100 and SOA-10 conditions. The onset of the second display and the points when the N2pc onset criterion value was reached are marked by stars and circles, respectively. There was a small target N2pc onset delay in the two color task, which was more pronounced for H2 targets. SOA = stimulus onset asynchrony.

demonstrating that this increase was similar in size in both SOA conditions.

Figure 4 also shows that N2pc amplitudes tended to be smaller in the two color task relative to the one color task. This was tested in an ANOVA of N2pc mean amplitudes measured in a 80-ms interval centered around the peak of the N2pc component for a particular experimental condition with the factors task and SOA. There was no significant main effect of task, $F(1, 11) = 3.3, p = .096$, indicating that the N2pc amplitude decrease in the two color task was not reliable. There was also no effect of SOA, $F(1, 11) < 1$, and no interaction between task and SOA, $F(1, 11) = 1.6, p = .226$, for N2pc amplitudes.

Discussion of Experiment 1

The findings from the one color task confirmed the observations from our previous study (Eimer & Grubert, 2014b). N2pc components were elicited by the first and second target in each trial, and

the temporal separation of these two N2pc components closely matched the objective time interval between the two successive search displays. The onset difference of the N2pc to H1 and H2 targets was 110 ms in the SOA-100 condition and 11 ms in the SOA-10 conditions. These findings demonstrate that the allocation of attention to new target objects can be triggered extremely rapidly, even when attention had been directed to another object just a few milliseconds earlier. The fact that the N2pc components to H1 and H2 targets in the SOA-10 condition overlapped in time, and were identical in amplitude (see Figure 2) provides strong evidence for the parallel allocation of attention to multiple target objects. If attention had to be de-allocated from its previous position before it could be directed to a new target location, as implied by strictly serial models of attentional object selection, the N2pc to H1 targets should have been very small and short-lived in the SOA10 condition, and should show only minimal temporal overlap with the N2pc to H2 targets. There was no evidence for

this in the one color task, which strongly suggests that attention was allocated in parallel and independently to the two successive target objects in this task. The fact that the onset latency difference between the N2pc components to H1 and H2 targets in the SOA10 condition (11 ms) matched the objective interval between these two targets suggests that both were selected independently, and the two parallel selection processes followed their own distinct time course.

The temporal sequence of N2pc components to H1 and H2 targets in the two color task closely resembled the pattern observed in the one color task. This observation shows that the speed with which the two successively presented target objects could be selected was not strongly affected when two colors were task relevant and there was always a color change between the first and second target. The onset latency of the N2pc to targets in the first display (212 ms) shows that these targets were selected rapidly, despite the fact that their exact color was not predictable. In both SOA conditions, the onset latency differences between the two N2pc components to H1 and H2 targets were only 20 to 25 ms longer than the objective onset asynchrony between the two displays in the two color task. This demonstrates that attention was rapidly allocated to a new color-defined target object, even though its color always differed from the target that was selected first, and even when the SOA between the two targets was extremely brief (10 ms). The observation that the N2pc components to H1 and H2 targets in the SOA–10 condition of the two color task were equal in size and overlapped in time (see Figure 3, bottom panel) strongly suggests that analogous to the one color task, these two targets were selected independently and in parallel.

There were however small but systematic N2pc onset latency differences between the one color and two color tasks. The N2pc to target objects in the first display was delayed by approximately 10 ms in the two color task. An N2pc onset delay for two color as compared to single color search also was observed in our previous study (Grubert & Eimer, 2013) where participants searched for color-defined target digits that appeared together with a gray distractor object in the opposite visual field, indicating that attentional target selection is triggered more rapidly when it can be guided by a unique color-specific attentional template. The N2pc onset delay observed for H1 targets in the two color task relative to the one color task of the present experiment could be due to the fact the observers did not know which of the two possible target colors would appear in the first display, or the fact that two different colors were known to be task relevant on each trial. These two alternatives were tested in Experiment 2.

The onset delay of the N2pc to H2 targets in the two color task relative to the one color task was slightly longer (approximately 30 ms) than the corresponding N2pc delay for H1 targets (10 ms), and the interval between the two N2pc components to H1 and H2 targets was therefore increased in the two color relative to the one color task. In other words, the attentional selection of H2 targets was delayed by an additional 20 ms in the two color task, and the size of this delay did not differ between the SOA–100 and SOA–10 conditions.² These findings are difficult to reconcile with previous claims that only one attentional template can be active at any given moment (e.g., Olivers et al., 2011), and that it may take up to 300 ms to switch between different attentional templates (Dombrowe et al., 2011). If the attentional selection of H2 targets in the two color task was based on a top-down controlled switch to

a new color-specific attentional template, color switch costs on N2pc latencies to H2 targets should have been much larger than was actually observed, in particular for the SOA–10 condition.

An alternative account that is more consistent with the results of Experiment 1 is that when target objects are defined by one of two equally likely colors, two color-specific attentional templates can operate simultaneously. In this scenario, the delay of N2pc components to H1 targets in the two color task relative to the one color task, and the presence of additional color switch costs for the N2pc to H2 targets in this task both reflect competitive interactions between two simultaneously active attentional templates. Competition between two color templates in the two color task generally reduces their activation level relative to a unique color template in the one color task, resulting in a small but systematic delay of attentional object selection. If the activation of one color template increases during the attentional selection of the first target, the activation of the other template will show a corresponding decrease. This should delay the selection of the second target in the two color task, as reflected by the additional N2pc onset delay of 20 ms observed in this task.

Experiments 2 and 3 were conducted to test this template competition account against an alternative rapid template switch hypothesis. Proponents of the view that only a single color-specific attentional template can be active at any time, and that the sequential selection of different target colors requires a switch between templates could argue that such a switch can occur much more rapidly than has previously been assumed. In the two color task of Experiment 1, the sequence of the two successively presented target colors varied randomly across trials, but the color of the second target was predictable once the first target had been presented. If rapid shifts between color-specific attentional templates were possible under such conditions, they should guide target selection even more efficiently in a two color task where the colors of the first and second target item are always the same and therefore known in advance. This was tested in Experiment 2.

Experiment 2

Participants performed the one color task and two variants of the two color task. One version was identical to the two color task of Experiment 1, where the sequence in which the two target colors appeared varied unpredictably across trials (two color variable). In the new fixed-sequence version of the two color task, the targets in the first and second display differed in color, but the respective colors of the first and second target were always the same (e.g., red targets followed by green targets). To maximize the opportunity for participants to perform a top-down controlled switch from one particular color template to another, only the longer of the two SOA conditions (100 ms) tested in Experiment 1 was employed in Experiment 2.

² To determine whether the N2pc delay to H2 targets in the two color task was linked to an increased N2pc onset latency variability in this task, we performed RT-based median split analyses, and computed N2pc waveforms for H2 targets on trials with fast and slow RTs, separately for the one and two color tasks. The N2pc to H2 targets emerged earlier on one color trials with slow responses than on two color trials with fast responses in both SOA conditions, confirming that N2pc components were consistently delayed across all trials in the two color task.

The small but reliable delay of N2pc components to H1 targets observed in Experiment 1 for the two color task relative to the one color task could be due to the fact that the color of the first target was unpredictable, and no specific color template could therefore be prioritized in advance. If this was the case, no such N2pc onset delay should be found for H1 targets in the two color fixed task, where the color of the first target was constant and therefore fully predictable. If the additional delay of N2pc components to H2 targets observed in the two color task of Experiment 1 reflects the time demands of a rapid switch between two color specific attentional templates, such a switch should arguably operate even more efficiently when participants know the target color sequence in advance. In this case, the N2pc to H2 targets should emerge earlier in the fixed relative to the variable version of the two color task. No such N2pc onset latency difference between these two versions of the two color task should be observed if the delayed N2pc to H2 targets during two color search reflects competitive interactions between two simultaneously active search templates.

Method

Participants. Thirteen paid participants were tested. One of them was excluded from analysis due to excessive eye movement activity. The remaining 12 participants were aged between 23 and 41 years (M age 32.7 years; $SD = 5.7$ years). Six were women, and three were left-handed. All had normal or corrected-to-normal vision and normal color vision.

Stimuli and procedure. There were three task conditions. The one color task and the two color variable task were identical to the one color and the two color tasks of Experiment 1 (SOA–100 conditions). In the new two color fixed task, the color of the target items in the first and second display remained constant across all trials. Six participants searched for red and green targets in both two color tasks, and the other six searched for blue and yellow targets in these two tasks. Each of these two target colors appeared randomly in the first or second display in the two color variable task. In the two color fixed task, there were four possible target color sequences (red → green, green → red, blue → yellow, yellow → blue). Each of these was assigned to three participants. The target color in the one color task (red, green, blue, or yellow) was counterbalanced across participants, and always differed from the colors that were task relevant in the two color tasks. Six successive blocks with 64 trials per block were run for each task, resulting in a total number of 18 blocks. Six participants started the experiment with the one color task, three with the two color variable task, and three with the two color fixed task. In all other respects, procedures were identical to Experiment 1.

EEG recording and data analyses. These were identical to Experiment 1, except that analyses were now conducted for three task conditions. Artifact rejection procedures led to the exclusion of 7.4%, 7.5%, and 8.0% of all trials in the one color, two color fixed, and two color variable tasks, respectively. All t tests are two-tailed and Bonferroni-corrected where necessary. As in Experiment 1, N2pc mean amplitudes were measured for an 80-ms interval centered on the peak latencies for a particular experimental condition (from 40 ms before to 40 ms after the N2pc peak). N2pc mean amplitude windows for H1 trials were 184 to 264 ms (one color), 204 to 284 ms (two color variable), and 196 to 276 ms (two color fixed). For H2 trials, the respective time windows were

304 to 384 ms (one color), 325 to 405 ms (two color variable), and 336 to 416 ms (two color fixed).

Results

Behavioral performance. The removal of anticipatory or very slow responses resulted in the exclusion of less than 0.2% of all trials. Table 1 shows RTs and error rates for the different task conditions of Experiment 2. There was a main effect of task (one color, two color variable, two color fixed) for RTs on trials with correct responses, $F(2, 22) = 16.8, p < .001$. Participants responded more than 100 ms faster in the one color task (575 ms) relative to the variable and fixed versions of the two color task, where RTs were virtually identical (680 ms and 679 ms, respectively). Same responses on trials where the alphanumerical categories of the two target items matched were faster than different responses on category-mismatch trials (628 ms vs. 661 ms), resulting in a main effect of target category, $F(1, 11) = 18.3, p < .001$. An interaction between target category and task, $F(2, 22) = 4.8, p = .019$, indicated that this RT difference was larger in the two versions of the two color task (37 ms) than in the one color task (24 ms). Errors tended to be more frequent in the variable and fixed versions of two color task (4.9% and 4.4%) relative to the one color task (3.6%), but there was no significant effect of task on error rates, $F(1, 11) = 1.4, p = .267$.

N2pc components. Figure 5 shows N2pc difference waveforms obtained by subtracting ERPs at posterior electrodes PO7/8 ipsilateral to the side of the horizontal target-color item in the first display (H1, left panel) or in the second display (H2, right panel) from contralateral ERPs, separately for the three tasks. As in the SOA–100 conditions of Experiment 1, N2pc components to H1 targets preceded N2pc components to H2 targets by approximately 100 to 130 ms. N2pc onset latency differences between H1 and H2 targets were 102 ms, 118 ms, and 133 ms, in the one color, two color fixed, and two color variable tasks, and these differences were all significant, all $t_c(11) > 17.1$, all $p < .001$. N2pc mean amplitudes to H1 and H2 targets were assessed by ANOVAs conducted separately for the three tasks with the two factors display sequence (H1 vs. H2 trials) and laterality (electrode ipsilateral vs. contralateral to the side of the horizontal target). All three ANOVAs revealed main effects of laterality, $F_s(1, 11) > 17.1, p_s < .003$, confirming reliable N2pc components to H1 and H2 targets in all three tasks. None of the Laterality × Display Sequence interactions reached significance, $F_s(1, 11) < 4.0, p_s > .073$, indicating that N2pc amplitudes did not differ systematically between H1 and H2 targets.

Onset latency differences of N2pc components between the three tasks were assessed by separate analyses for H1 and H2 targets. The onset of the N2pc to H1 targets differed reliably across the three tasks, $F_c(2,22) = 5.6, p = .011$. Follow-up t tests revealed that the N2pc emerged earlier in the one color task relative to the two color variable task (205 ms vs. 214 ms), $t_c(11) = 3.0, p = .037$, confirming the results of Experiment 1. More important, the onset latency of the N2pc to H1 targets in the new two color fixed task (206 ms) was statistically identical to the one color task, $t_c(11) < 1$, and was reliably earlier than the latency of the N2pc to H1 targets in the two color variable task, $t_c(11) = 3.0, p = .039$. The latency of N2pc components to H2 targets also varied reliably across tasks, $F_c(2,22) = 12.0, p < .001$. Follow-up

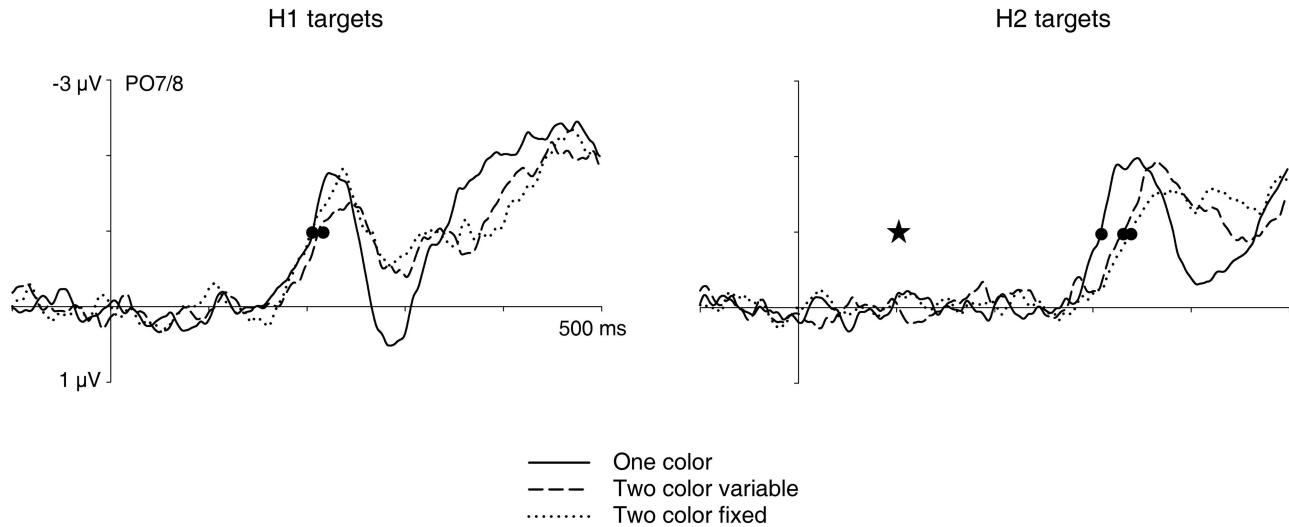


Figure 5. N2pc components obtained in response to H1 targets (left panels) and H2 targets (right panels) in the three different task conditions of Experiment 2. N2pc difference waves were obtained by subtracting ipsilateral from contralateral event-related potentials (ERPs). The onset of the second display is indicated by a star, and the points when N2pc onset criterion values were reached by circles. For H1 targets, N2pc onset is delayed in the two color variable task. For H2 target, N2pc components emerge later in both versions of the two color task relative to the one color task. H1 = horizontal target in the first display; H2 = horizontal target in the second display.

t tests confirmed the observation from Experiment 1 that the N2pc to H2 targets emerged earlier in the one color task relative to the two color variable task (302 ms vs. 333 ms), $t_c(11) = 4.6$, $p = .002$. Critically, the N2pc to H2 targets in the new two color fixed task (onset latency: 338 ms) was also reliably delayed relative to the one color task, $t_c(11) = 4.6$, $p = .002$, and there was no reliable N2pc onset latency difference between the two color variable and two color fixed task, $t_c(11) < 1$.

Discussion of Experiment 2

N2pc components to H1 targets emerged about 10 ms later in the two color variable task relative to the one color task, and there was an additional delay of about 20 ms for H2 targets in the variable version of the two color task. These observations perfectly replicate the findings from the SOA-100 conditions of Experiment 1, and confirm the existence of small but systematic delays of color-guided attentional target selection during two color as compared to single color visual search. The N2pc results for the new fixed version of the two color task provide additional insights into the factors responsible for these delays. The N2pc to H1 targets in the two color fixed task emerged at the same time as the N2pc in the one color task, and reliably earlier than the N2pc to H1 targets in the variable version of the two color task (Figure 5, left panel). This demonstrates that the speed with which the first color-defined target was selected was determined by the predictability of its color. Because the first target color was known in advance both in the one color task and two color fixed tasks, participants could selectively prioritize a color-specific search template prior to the presentation of this search display. This was not possible in the two color variable task, where the color of the first target varied unpredictably across trials. The fact that two

different color targets had to be selected in rapid succession in the two color fixed task while a single color was relevant in the one color task apparently did not affect the selection speed for H1 targets. This will be further discussed below.

The N2pc to H2 targets was reliably delayed in the fixed version of the two color task relative to the one color task, and emerged at the same time as the N2pc to H2 targets in the two color variable task (Figure 5, right panel). If the selection of H2 targets in the two color task had been based on a switch between color-specific attentional templates, this switch should presumably have occurred more rapidly when the target color sequence was constant and thus fully predictable, resulting in earlier N2pc components to H2 targets in the fixed relative to the variable version of the two color task. The fact that no such N2pc latency differences were found in Experiment 2, and the observation that RTs were also virtually identical for both versions of the two color task appears inconsistent with this rapid template switch hypothesis. Proponents of this hypothesis could still argue that even in the variable version of the two color task, the color of the second target was not completely unpredictable, but was determined by the color of the first target. Participants may therefore still have been able to activate a new color-selective search template after detecting the target color in the first display. To provide a decisive test of the rapid template switch hypothesis, the variable version of the two color task needs to be compared to another version of this task where the color of the second target is entirely unpredictable. This was done in Experiment 3.

Experiment 3

In the new fully random version of the two color task, the colors of the first and second target were selected randomly and inde-

pendently on each trial. As a result, the target in the second display could have the same color or a different color as the target in the first display (color repetition vs. color change trials). Furthermore, the color of the first target was now entirely uninformative with respect to the color of the second target. Behavioral performance and N2pc components in this new two color random task were compared to the variable version of the two color task that was identical to the task used in Experiments 1 and 2. The SOA between the two successive displays was always 100 ms.

If the selection of the second target in the two color variable task was based on a rapid switch between two color-specific templates in the interval between the two displays, it should be more efficient in this task relative to the random version of the two color task, where the color of the second target remained uncertain even after the first target has been presented. As a consequence, N2pc components to H2 targets should be delayed in the random as compared to the variable version of the two color task. This should not be the case if two color-specific attentional templates can be simultaneously active, and if the N2pc delays to H2 targets in the two color task relative to the one color task are due to competitive interactions between these templates. The N2pc to H2 targets should emerge at the same time on color change trials in the two color random task as in the two color variable task (where target color always changed between the two displays). If the color-guided attentional selection of the first target results in a competitive advantage for the corresponding color template, the attentional selection of the second target should be more efficient on color repetition as compared to color change trials in the two color random task, resulting in an earlier onset of N2pc components to H2 targets on color repetition trials.

Method

Participants. Fifteen paid participants were tested. Three were excluded due to excessive eye movement activity. The remaining 12 participants were aged between 20 and 42 years (M age 30.9 years; $SD = 6.2$ years). Seven were women, and two were left-handed. All had normal or corrected-to-normal vision and normal color vision.

Stimuli and procedure. Two variants of the two color task were run, and the SOA between the first and second display was always 100 ms. The two color variable task was identical to Experiment 1 (SOA=100 condition) and Experiment 2. In the new two color random task, the color of the target in the first and second display was determined randomly and independently on each trial. As a result, the two targets had the same color on half of all trials (color repetition trials), and differed in color on the other half (color change trials), and the color of both H1 and H2 targets was always unpredictable. Six participants searched for red and green targets in both tasks, and the other six for blue and yellow targets. The two color variable task was performed in six successive blocks of 64 trials. For the new two color random task, 12 blocks of 64 trials were run, to equate the number of color repetition and color change trials to the number of trials obtained in the two color variable task, where there was always a color change between the first and second target. Six participants completed the two color variable task prior to the two color random task, and this order was reversed for the other six

participants. In all other respects, procedures were identical to Experiments 1 and 2.

EEG recording and data analyses. These were identical to Experiments 1 and 2, except that separate analyses were conducted for color repetition and change trials in the two color random task. Artifact rejection led to the exclusion of 8.9% and 10.7% of all trials in the variable and random versions of the two color task. N2pc mean amplitudes were measured in the 80-ms time window centered on the N2pc peak latency for each experimental condition separately (from 40 ms before to 40 ms after the N2pc peak). N2pc mean amplitude windows for H2 targets were 380 to 460 ms (variable task), 320 to 400 ms (random task: color repetition), and 386 to 466 ms (random task: color change).

Results

Behavioral performance. Anticipatory or exceedingly slow responses led to the exclusion of less than 0.3% of all trials. Table 1 shows RTs and error rates for the different task conditions of Experiment 3. RTs on trials with correct responses were compared between the two color variable task and color repetition versus color change trials in the two color random task. There was a main effect of task condition, $F(2, 22) = 14.1, p < .001$. RTs were faster on color repetition trials in the random task (635 ms) relative to color change trials in this task (708 ms) and RTs in the variable task (699 ms), $t_s(11) > 4.0, p_s < .007$. RTs in color change trials did not differ from RTs in the variable task, $t(11) < 1$. As in the first two experiments, same responses on category-match trials were faster than different responses on category-mismatch trials in the variable task (665 ms vs. 734 ms), as well as on color repetition trials (605 ms vs. 666 ms) and color change trials (678 ms vs. 739 ms), in the random task, resulting in a main effect of target category, $F(1, 11) = 31.6, p < .001$. There was no interaction between task condition and target category, $F(2, 22) < 1$. Error rates did not differ reliably between the variable task (7.6%) and color repetition or change trials (5.9% and 7.9%) in the random task, $F(2, 22) < 1$.

N2pc components. Figure 6 (left panel) shows N2pc difference waveforms obtained by subtracting ERPs at posterior electrodes PO7/8 ipsilateral to the side of the horizontal target-color item from contralateral ERPs for horizontal targets in the first display (H1 trials), separately for the variable and random versions of the two color task. The onset latency of N2pc components to H1 targets was virtually identical in both versions of this task (212 vs. 213 ms), $t_c(11) < 1$, which is unsurprising, given that the color of the first target was equally unpredictable in both tasks. In contrast, as shown in the difference waveforms of Figure 6 (right panel), there were systematic differences in the onset of N2pc components to H2 targets between color repetition and color change trials in the random task and the variable task, $F_c(2,22) = 144.9, p < .001$. The N2pc to H2 targets emerged earlier on color repetition trials in the random task (299 ms) relative to color change trials in the same task (343 ms) and to the variable version of the two color task (339 ms), $t_{c,s}(11) > 6.7, p_s < .001$. There was no N2pc onset difference between color change trials in the random task and the two color variable task, $t_c(11) < 1$. As can be seen in Figure 6 (right panel), N2pc components to H2 targets differed in size, $F(2, 22) = 7.6, p = .003$; they were larger for color repetition trials in the random task relative to the other two task conditions (random: color

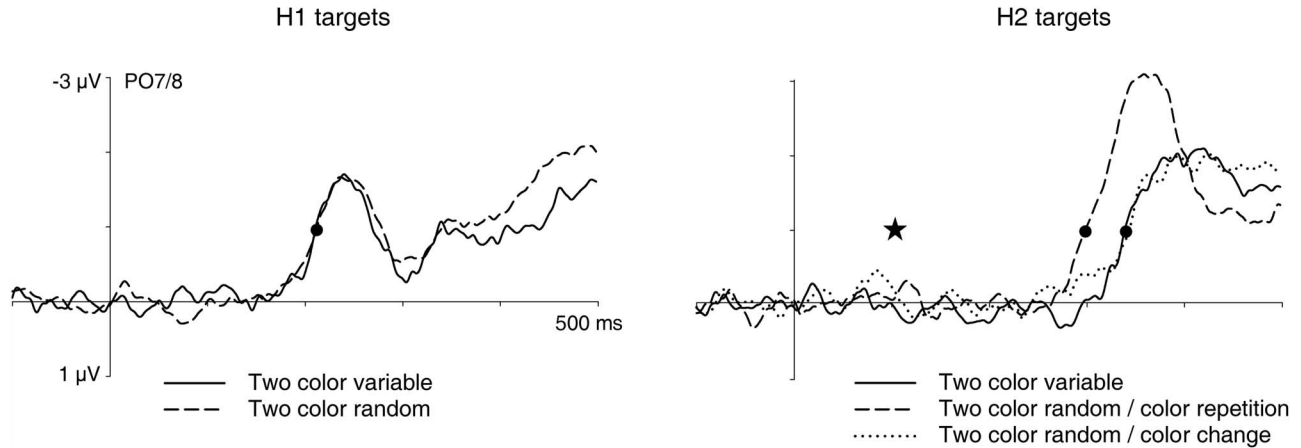


Figure 6. N2pc components obtained in Experiment 3 in response to H1 targets in the random and variable versions of the two color task (left panels) and to H2 targets in the two color variable task and on color repetition and color change trials in the two color random task (right panels). N2pc difference waves were obtained by subtracting ipsilateral from contralateral event-related potentials (ERPs). The star marks the onset of the second display, and the circles mark the points when N2pc onset criterion values were reached. N2pc components to H2 targets emerged earlier on color repetition trials in the two color random task than in color change trials in this task and in the two color variable task. H1 = horizontal target in the first display; H2 = horizontal target in the second display.

change and variable task), and these amplitude differences were significant, $t_s(11) > 4.8$, $p_s < .004$.

Discussion of Experiment 3

The results of Experiment 3 were clear-cut. In contrast to the predictions of the rapid template switch hypothesis, N2pc components to H2 targets did not emerge earlier in the variable version of the two color task, where the color of the second target was predictable once the first target was presented, than in the random version of this task where the second target color remained uncertain. The absence of any performance or N2pc onset latency differences between the two color variable task and color change trials in the two color random task rules out the idea that participants rapidly switched between two color-specific search templates when the color of the second target was predictable, and that the delay of N2pc components in the two color task reflects the time costs associated with such a template switch. Experiment 3 also provided additional evidence for the alternative hypothesis that competitive interactions between simultaneously active attentional templates are responsible for the N2pc onset delays observed for H2 targets in the two color task. N2pc components to H2 targets emerged earlier on color repetition trials relative to color change trials in the two color random task (see Figure 6), and RTs were also considerably faster on these trials. This demonstrates that the selection of H2 targets was more efficient on trials where it could be guided by the same template that had already been activated during the preceding selection of the first target than on trials where the target template was not involved in this earlier selection episode.

General Discussion

The aim of the present study was to assess the speed of allocating attention to two successively presented target objects under

conditions where attention cannot be controlled by a single feature-specific attentional template. We measured the N2pc component as a marker of attentional object selection in a one color task where both targets were defined by the same color and in different versions of a two color task where these two targets could have one of two possible colors. If the requirement to simultaneously maintain two color-specific attentional templates generally reduces the efficiency of attentional target selection (e.g., Grubert & Eimer, 2013; Houtkamp & Roelfsema, 2009; Stroud et al., 2011), task performance should be impaired in the two color task, and the attentional selection of the two successively presented targets should operate much more slowly, as reflected by strongly delayed N2pc components relative to the one color task. The results of Experiment 1 demonstrated that the attentional selection of color-defined target objects that are presented in rapid succession remains remarkably fast and efficient even when it cannot be guided by a single feature-specific attentional template. Relative to the one color task where all targets were defined by a single known color, the selection of the first target was delayed by approximately 10 ms when its color was not known in advance, and the selection of a second target was delayed by an additional 20 ms when its color differed from the color of the first target. This was the case both for a 100-ms SOA between the two targets and when this SOA was reduced to 10 ms. Even though these N2pc onset latency differences between the one and two color tasks are theoretically important, the fact remains that the two target objects were still selected extremely rapidly in the two color task, and the time course of their selection closely matched the objective time interval between the two displays.

The results of Experiments 2 and 3 ruled out the hypothesis that the delayed onset of N2pc components to H2 targets in the two color task relative to the one color task reflects the time demands of rapid switches between two color-specific attentional templates. In these two experiments, the SOA between the first and second

target display was always 100 ms, to provide sufficient time for participants to initiate a top-down controlled template switch when the color of the second target was predictable. However, the N2pc delay to H2 targets in the two color task was unaffected by whether the target color sequence varied randomly across trials or remained constant and was therefore known in advance (Experiment 2), and by whether the color of the second target item was predictable or unpredictable once the first target had been presented (Experiment 3). If the selection of the second target on each trial had been guided by a top-down controlled switch to a new color template, its speed should have been strongly affected by the predictability of the second target's color. The absence of any such color predictability effects on N2pc onset latencies to H2 targets in the two color task is inconsistent with this rapid template switch hypothesis. The pattern of N2pc results observed in Experiments 2 and 3 with an SOA of 100 ms between the two displays also implies that top-down controlled template switches cannot account for the N2pc onset delay to H2 targets in the SOA10 condition of Experiment 1, as such an extremely short SOA will provide even less opportunity for such switches to be initiated.

If the rapid template switch hypothesis is no longer available, it can be concluded that the remarkable speed of attentionally selecting two successively presented target objects defined by two different colors reflects the ability to simultaneously activate two different color-specific templates (see also Beck, Hollingworth, & Luck, 2012, for a similar conclusion based on eye movement patterns observed during single color and two color visual search). The speed with which a specific target is selected is modulated by competitive interactions between these templates. Increases in the activation level of one color template during the attentional selection of the first target and corresponding decreases in the activation of the other template facilitate the selection of a second target that matches the color of the first target, and delay the selection of a target in a different color (see also Olivers et al., 2011, for a similar claim that simultaneously maintained working memory representations can differ in their activation levels). This can account for the N2pc onset differences to H2 targets in the one and two color tasks, and also for the observation of Experiment 3 that N2pc components to H2 targets in the two color random task emerged earlier on color repetition as compared to color change trials. Even when two color templates are simultaneously active, advance knowledge about the color of an upcoming target can enhance the activation of one of these templates, so that target selection efficiency becomes similar to single-color search. Evidence for this was found in the two color fixed task of Experiment 2, where the target color sequence was known in advance, and the N2pc to H1 targets emerged at the same time as the N2pc to H1 targets in the one color task. Even though the color of the second target was just as predictable in this two color fixed task, the N2pc to H2 targets were delayed, reflecting a competitive disadvantage of the second color template as the result of a color switch between the first and the second target.

It is important to note that the N2pc component reflects an early stage of attentional object selection in ventral visual cortex, which is triggered by perceptual evidence for the presence of task-relevant attributes obtained during the rapid feedforward processing of visual information (e.g., Eimer, 2014), and is controlled in parallel and independently by signals from different feature channels (Eimer & Grubert, 2014a). The current findings demonstrate

that this early stage of spatially selective attentional processing still operates fast and efficiently even when target-defining features are not fully predictable and change rapidly between objects. Previous behavioral findings that suggest severe capacity limitations of attentional templates (e.g., Houtkamp & Roelfsema, 2009; Stroud et al., 2011) and substantial template switch costs (Dombrowe et al., 2011) are likely to be associated with processing stages that follow the rapid attentional selection of visual target objects, as reflected by the N2pc component. For example, the encoding and maintenance of selected objects in visual working memory, the subsequent identification of these objects, and the selection of manual or saccadic response could all be impaired in tasks where target-defining features are variable and change between successive selection episodes. In fact, the behavioral results obtained in the present study do provide evidence that the change of target-defining features across successive selection episodes can affect processing stages beyond the rapid allocation of attention to target objects. In Experiments 1 and 2, RTs were delayed by more than 100 ms in the two color relative to the one color tasks. In the two color random task of Experiment 3, RTs were more than 70 ms slower on color change as compared to color repetition trials. These RT differences were considerably larger than the corresponding N2pc latency differences between these task conditions, suggesting that they were at least in part generated after the initial target selection stage.

Similar performance costs linked to feature changes between visual target objects are well documented in the literature. In tasks where observers have to classify stimuli with respect to one dimension and ignore another dimension, performance is impaired when features in the irrelevant dimension change randomly across trial (e.g., Garner, 1970). This is usually interpreted as a failure in the attentional separation of relevant and irrelevant dimensions (e.g., Garner, 1988; Garner & Felfoldy, 1970). Along similar lines, observers often fail to ignore changes in task-irrelevant dimensions during same-different comparisons between multidimensional objects, and this can interfere with the comparison process (e.g., Egeth, 1966). This interference has been attributed to response compatibility, which delays the selection of same responses on trials where the two objects differ on the irrelevant dimension and of different responses on trials where both objects share the same task-irrelevant feature (e.g., Garner, 1988). However, response compatibility cannot account for the slow RTs observed in the two color tasks of the present study. In all three experiments, RTs were faster on trials where the alphanumeric category of two successively presented targets matched relative to category-mismatch trials. More important, this RT advantage for same over different responses was reliably larger in the two color tasks of Experiments 1 and 2, despite the fact that there was always a color change between the two targets, which should have produced response compatibility benefits for different responses.

If the RT costs in the two color task are not linked to response selection processes, they may instead be generated at the stage where the two target objects are compared to determine a category match or mismatch. Hyun, Woodman, Vogel, Hollingworth, and Luck (2009) demonstrated that the presence of task-irrelevant changes can slow the comparison between sample and test stimuli in a change detection task. Based on this observation, these authors argued that comparisons between successively presented visual objects depended on a slow limited-capacity matching process in

working memory that follows the attentional selection of these objects, and could be affected by changes in a task-irrelevant dimension. The dissociation observed in the present experiment between target N2pc onset latencies (which showed only small costs in the two color tasks) and the target RTs (which revealed more substantial impairments) is consistent with this hypothesis. The fact that object color was irrelevant for the category matching task, but was relevant for the attentional selection of the to-be-matched target objects may have increased the RT costs of color changes on the category matching process in the present study. In this context, it is interesting to note that in our previous N2pc study of one color versus two color search (Grubert & Eimer, 2013) where participants simply had to identify color-defined targets and no comparison was required, the target N2pc onset delay between the two tasks matched the RT difference between them, suggesting that in the absence of working memory comparison processes, performance costs during multiple-feature search can be fully accounted for by the reduced speed of attentional target selection processes. The exact nature of the effects of feature variability on the cognitive and neural mechanisms that are involved in object comparison processes needs to be clarified in future experiments.

We previously found that when target objects appeared in rapid succession at different locations in the visual field, focal attention can be allocated rapidly and independently to multiple objects (Eimer & Grubert, 2014b). The current results show that this fast mode of selective spatial attention is not restricted to situations where target objects are defined by a unique and constant attribute, and their selection can therefore be guided by a single feature-specific attentional template. They challenge the widely held assumption that visual attention operates in a strictly serial fashion by demonstrating that even when target-defining features are not fully predictable and change between successive selection episodes, attention can still be allocated extremely rapidly to multiple objects. They also challenge the hypothesis that only a single feature-specific attentional template can be active at any moment in time. The control processes that are responsible for the allocation of focal attention to task-relevant visual objects appear to operate much faster and more flexibly than is commonly thought.

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