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# Target switch costs in visual search arise during the preparatory activation of target templates

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**Abstract**

Prior research on task switching has shown that the reconfiguration of stimulus–response mappings across trials is associated with behavioral switch costs. Here, we investigated the effects of switching representations of target-defining features in visual search (attentional templates). Participants searched for one of two color-defined target objects that changed predictably every two trials (Experiment 1) or every four trials (Experiment 2). Substantial costs were observed for search performance on target switch relative to target repeat trials. Preparatory target template activation processes were tracked by measuring N2pc components (indicative of attentional capture) to a rapid series of task-irrelevant color singleton probes that appeared during the interval between search displays, and either matched the currently relevant or the other target color. N2pcs to relevant target color probes emerged from 800 ms before search display onset on target repetition trials, reflecting the activation of a corresponding color template. Crucially, probe N2pcs only emerged immediately before target onset on target switch trials, indicating that preparatory template activation was strongly delayed. In contrast, irrelevant color singleton probes did not trigger N2pcs on either repeat or switch trials, suggesting the absence of any target template inertia across trials. These results show that switching the identity of search targets delays preparatory target template activation and impairs subsequent attentional guidance processes. They suggest that performance costs on switch versus repeat trials are associated with differences in the time course of task preparation.

**KEYWORDS**

attentional templates, event-related potentials, N2pc, selective attention, task switching, visual search

## 1 | INTRODUCTION

The ability to change cognitive task settings and behavioral responses when this is required by a change in circumstances is a central function of human cognitive control (e.g., Shallice & Cooper, 2011). The evolution of cognitive control mechanisms has enabled humans to interact with the external world flexibly and adaptively, in

ways that sets us apart from all other animals. In the lab, this remarkable ability is often studied by investigating how humans prepare to perform a specific task, and how they reconfigure a particular task set when their goals change. The task switch paradigm (Allport et al., 1994; Jersild, 1927) has become a popular tool to explore the mechanisms involved in activating specific task sets and changing them when needed. In a typical task-switching experiment, participants are instructed to perform one of two possible tasks. On any given trial, the task either repeats or switches relative to the previous trial. The crucial finding in such experiments is that response times (RTs) are slower and errors often more frequent on switch trials as compared to repeat trials ("switch costs"; see Kiesel et al., 2010; Monsell, 2003; Vandierendonck et al., 2010, for reviews).

The mechanisms that produce such switch costs have been investigated extensively because it is assumed that these costs reflect the operation of domain-general cognitive control processes that are involved in the selection and coordination of many different types of tasks. One widely used procedure to study task switches is the alternating-runs paradigm, where participants perform two tasks in a constant order (e.g., AABBAABB, see Rogers & Monsell, 1995). The comparison of trials where a task is repeated and trials where it changed revealed substantial behavioral switch costs, in spite of the fact that task switches were fully predictable. Such costs are assumed to reflect the time demands of preparatory endogenous task-set reconfiguration processes (e.g., Meiran et al., 2000; Monsell et al., 2000). The observation that these costs become smaller but remain reliably present even when participants are given several seconds to prepare for each task (Rogers & Monsell, 1995) suggests that task switching cannot be fully completed on the basis of purely endogenous preparation mechanisms, but also includes a stimulus-driven component. To fully establish a task set, a new task has to be performed at least once (see also Rubinstein et al., 2001). In line with this hypothesis, experiments with longer alternating runs (e.g., AAAABBBB in Monsell et al., 2003) have found performance costs only for the first trial after a switch, but not on subsequent trials of the same run. It has also been suggested that such costs may emerge more passively, as a result of the persistence of a previously active task set (task-set inertia; e.g., Allport & Wylie, 1999). Any persisting irrelevant task set activation may interfere with the operation of a new task set, and thus produce switch costs that are unrelated to the preparatory activation of the other task (see Kiesel et al., 2010, for further discussion). Active endogenous task-set reconfiguration and passive task-set inertia are not mutually exclusive; it is possible that both contribute to empirically observed switch costs (Monsell, 2003; see also Imburgio & Orr, 2021).

Most previous investigations of the processes involved in switching between task sets used procedures where tasks were defined in terms of the rules that associate particular stimuli and responses (e.g., categorizing digits with respect to their magnitude or parity, or categorizing words in terms of their meaning or color). However, there are many different types of task sets, which raises the question how task switching operates in such different contexts. For example, an important function of cognitive control is the guidance of selective attention in line with current intentions, which requires task sets that specify the relevance of particular objects or object features in a given context (e.g., Folk et al., 1992). For example, in visual search tasks, where multiple stimuli are present in a single display, targets are defined by one or more attributes that distinguish them from distractors. Such target-defining features are usually known in advance and are assumed to be represented as attentional templates (e.g., Duncan & Humphreys, 1992). Such templates can be activated prior to the onset of a search display, in order to guide attention to objects with target-matching features and facilitate the detection of search targets. Target templates are a particular type of task set that specifies object attributes that are relevant for current search goals, rather than mappings between stimuli and responses, as investigated in most previous task switching experiments (see Rushworth et al., 2002, for a study where both types of task settings were combined). Thus, the question arises whether switching between target templates also induces behavioral switch costs, and which mechanisms are responsible for such costs.

Several previous visual search studies have used tasks where participants had to find one of several possible target objects, and these studies have typically revealed performance costs on trials where the identity of the target changed relative to target repetition trials (e.g., Christie et al., 2015, Experiment 2; Dombrowe et al., 2011; Found & Müller, 1996; Grubert & Eimer, 2013; Juola et al., 2004; Olivers & Meeter, 2006). It remains unknown which mechanisms are responsible for these target switch costs, and at which stage they are generated (see Ort & Olivers, 2020, for discussion). Because target identity changed unpredictably across trials in most of these previous studies, participants could not strategically activate a particular target template while preparing for the next search episode. However, in tasks where the identity of an upcoming search target is predictable, target switch costs may be produced by processes that take place during the search preparation period, analogous to the processes investigated in standard task switching experiments. They could be the result of less

efficient endogenous template activation prior to target switch versus repeat trials. Such template switch costs would be analogous to the endogenous task-set reconfiguration processes postulated in the task switching literature (e.g., Monsell et al., 2000). But target switch costs could also be produced by the persistence of a previously active target template (i.e., task-set inertia; e.g., Allport & Wylie, 1999) interfering with the activation of the currently relevant template.

To investigate these possibilities, search tasks have to be employed where target switch and target repeat trials are fully predictable. The goal of the present study was to use such tasks in order to obtain new insights into preparatory target template activation and reconfiguration processes in visual search. To track target template activation processes in real time, we employed a rapid serial probe presentation (RSPP) paradigm that we used in several previous studies (Grubert & Eimer, 2018, 2020, 2023). In these experiments, participants searched for targets defined by a specific constant color. Search displays were preceded by a series of irrelevant probe displays that appeared in rapid succession throughout the interval between successive search displays. Some of these probe displays included a color singleton item that matched the current target color. These color probes will capture attention only when a corresponding target color template is active, but not at other times. To track the time course of target template activation by measuring probe-induced attentional capture, we recorded event-related potentials (ERPs) and computed N2pc components separately for each successive probe presented between two search displays. The N2pc is a negativity at posterior scalp electrodes triggered contralateral to attended objects in multi-stimulus displays. It usually emerges about 200 ms after stimulus onset, is generated in ventral extrastriate visual areas (Hopf et al., 2000), and reflects the rapid allocation of attention to candidate target objects (e.g., Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999; see Eimer, 2014, for a review). In our previous RSPP experiments, target color probes triggered N2pc components from about 1000 ms prior to the onset of the next search display, indicating that a corresponding color template was active during this period. Manipulating the predictable interval between two search displays changed the temporal pattern of probe N2pcs (Grubert & Eimer, 2018). They were triggered earlier when this interval was shorter than when it was longer, demonstrating that target template activation processes are sensitive to temporal expectations about search display onset. Importantly, no probe N2pcs were elicited by color singleton probes that did not match the current target color.

In one previous experiment (Grubert & Eimer, 2020), we employed this probe procedure in a task where observers searched for one of two color-defined targets. Target identity swapped on each trial (ABAB) and probes matching either of these two colors were randomly intermixed. Here, N2pcs emerged for both target color probes during search preparation, indicating that both color templates were active concurrently, even though only one of them was relevant for the next search episode. The co-activation of both templates in this experiment might have been a strategic choice, as target color changed on every trial (see also Grubert et al., 2017). Alternatively, it could have been the result of task-set inertia, that is, the persistence of the target color template that was relevant on the preceding trial, analogous to the persistence of previously relevant stimulus–response mappings postulated by Allport and Wylie (1999).

The ABAB design employed in this previous experiment (Grubert & Eimer, 2020) did not allow to compare and contrast target template activation processes prior to target switch and target repeat trials. In the current study, we therefore used an alternating-runs procedure analogous to Rogers and Monsell (1995). As before, search displays included one of two possible color-defined targets, but target identity now either repeated or switched across successive trials, in a fully predictable fashion. This allowed participants to activate a corresponding target color template in a preparatory fashion prior to the presentation of each search display. In Experiment 1, the target identity changed every second trial (i.e., AABB), so that target color repetitions and switches occurred on half of all trials. Color singleton probe displays were presented every 200 ms in the interval between two search displays, and each singleton probe was equally likely to match either of the two possible target colors (see Figure 1 for illustration).

With this AABB design, we could measure behavioral template switch costs for search performance, and also track the activation of both target color templates, separately for target switch and target repeat trials. Analogous to the findings by Rogers and Monsell (1995), we expected RTs to be slower and error rates higher on switch relative to repeat trials. The critical new question was whether target template activation processes observed during the preparation for the upcoming search episode would also differ between these two types of trials, as reflected by systematic differences in the pattern of probe N2pc components. If there are switch costs for the activation of the color template that is relevant for the next search display, this should be indicated by a delay in the emergence of N2pc components triggered by the corresponding color singleton probes on switch as compared to repeat trials, and/or an attenuation of N2pc amplitudes on switch trials. Furthermore, the presence of task-set inertia should be reflected by the presence of N2pcs in response to singleton probes that match the currently irrelevant target color,

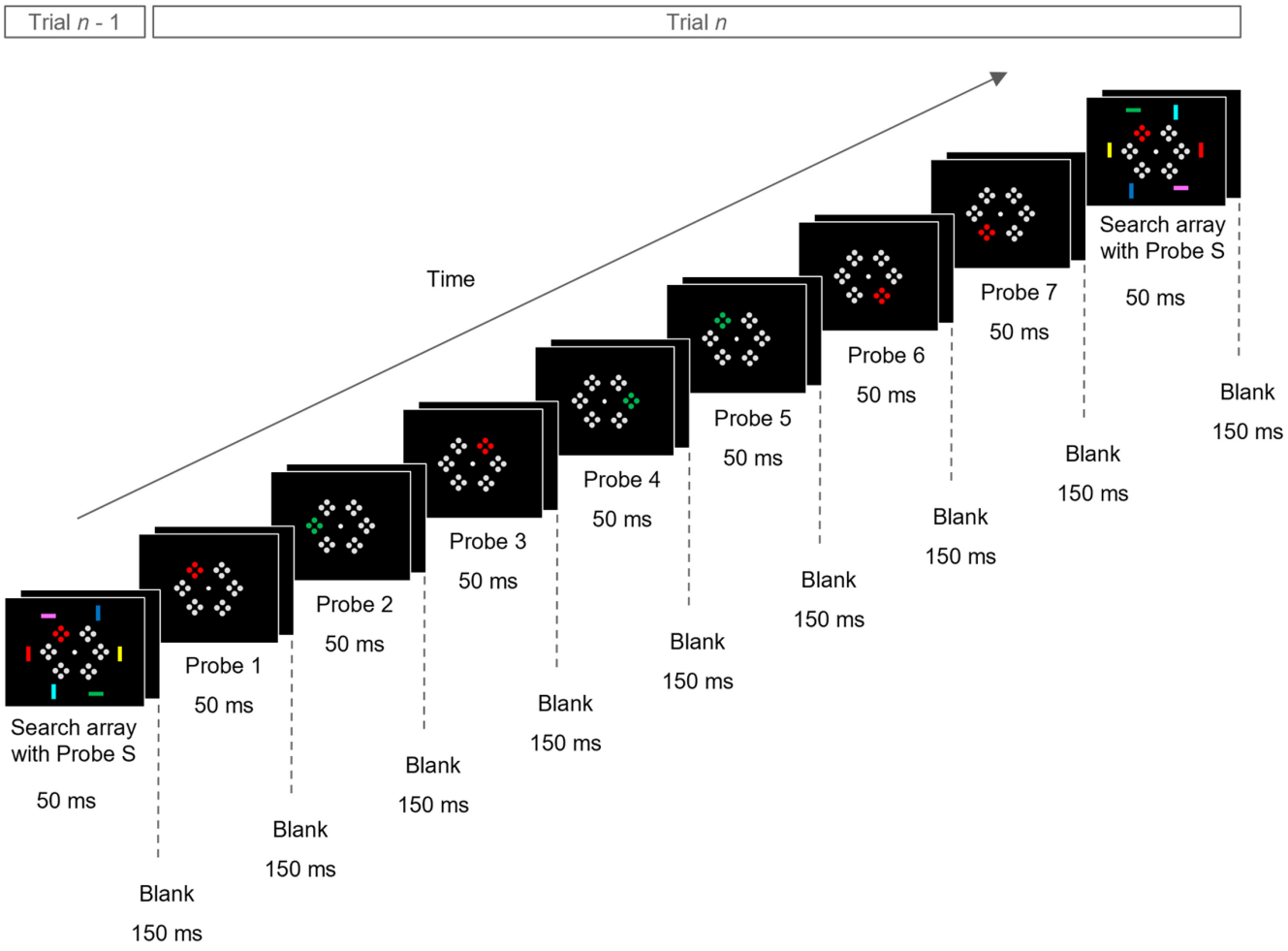


**FIGURE 1** Schematic illustration of the stimuli and presentation times in Experiment 1 and 2. Search displays contained two color-defined target bars (e.g., red, green) and four nontarget bars in four different nontarget colors (e.g., blue, yellow, pick, cyan). Importantly, only one of the two target color bars was response relevant in each trial. In Experiment 1, the color of the response relevant target changed after every second trial (e.g., red in trials 1–2, green in trials 3–4, red in trials 5–6, etc.), while it changed after every fourth trial in Experiment 2 (e.g., red in trials 1–4, green in trials 5–8, red in trials 8–12, etc.). Probe displays contained a color singleton that randomly matched one of the two possible target colors among five gray items. Probe displays were presented every 200 ms in the interval between two search displays (probes 1–7) and simultaneously with a search display (probe S). The items in the probe and search arrays were arranged on imaginary circles at an eccentricity of 0.5° and 1.4° from central fixation, respectively.

indicating the persistent activation of the corresponding target template. Such an effect should be primarily or even exclusively observed prior to target switch trials.

## 2 | EXPERIMENT 1

### 2.1 | Methods

#### 2.1.1 | Participants

Twenty-two paid participants were tested in Experiment 1. The experiment was approved by the Ethics Committee of the Psychology Department at Durham University and was conducted in accordance with the Declaration of Helsinki. Participants gave informed written consent prior to testing. Four participants were excluded from analysis due to excessive eye movement artifacts (>40% of trials were lost during artifact rejection). The remaining 18 participants were between 19 and 47 years of age (mean = 30.5, *SD* = 8.6). Fourteen participants were female and four were male. All participants were right-handed and had normal or corrected-to-normal vision and normal color vision (tested with the Ishihara color vision test; Ishihara, 1972). The sample size of 18 was calculated by means of an a priori power analysis using

MorePower 6.0.1 (Campbell & Thompson, 2012) to detect an interaction in a 2×2×7×2 factorial repeated measures ANOVA (within-subjects) with an assumed alpha of 0.05, power of 0.85, and a large effect size of 0.80.[1]

### 2.1.2 | Stimuli and procedures

Participants were sat in a dimly lit and sound attenuated Faraday cage with a 90 cm viewing distance from the monitor. Stimuli were presented on a 22-inch MSI Optix G272 LCD monitor with a 100-Hz refresh rate and a resolution of 1920×1080 pixels. PsychoPy (psychophysics software in Python; Peirce et al., 2019) was used on an LG Pentium PC running under Windows 10 to control stimulus presentation, timing, and response collection. Figure 1 illustrates the time course of stimulus events. All stimuli were presented on a black background with a constant central gray fixation point (CIE *x*,*y* color coordinates: 0.327/0.348; 0.2°×0.2° of visual angle). Each block contained 12 trials with eight stimulus displays that were presented in a continuous serial presentation stream. Each stimulus display was presented for 50 ms and followed by a 150 ms blank (200 ms stimulus onset asynchrony; SOA). The first seven displays in each trial each contained a probe display (probes 1 to 7), the eighth displays contained both the response-relevant search display and a probe display (probe S[earch][2]).

Search arrays were presented at an eccentricity of 1.4° from central fixation and contained six vertically (0.2°×0.6°) or horizontally (0.6°×0.2°) oriented bars at the 1, 3, 5, 7, 9, and 11 o'clock positions of an imaginary circular clock face. The orientations of the six bars were selected independently and randomly in each search display. Each bar had a different color which was randomly allocated from the set of red (0.610/0.321), green (0.273/0.624), blue (0.172/0.181), yellow (0.435/0.490), cyan (0.222/0.313), and pink (0.483/0.246). All colors were equiluminant (~11.9 cd/m$^2$). Red, green, blue, and yellow were the possible target colours. Each participant was assigned two of these colors as target colors. Each of the six possible target color pairs (red/green, red/blue, red/yellow, green/blue, green/yellow, blue/yellow) was assigned to three participants. The other two colors (cyan and pink) served as nontarget colors only. Participants' task was to report the orientation (vertical/horizontal) of the target color bar in each trial by pressing the up/down arrow keys on a standard keyboard. Critically, the response-relevant target color switched after every second trial (e.g., red in trials 1 and 2, green in trials 3 and 4, red in trials 5 and 6, etc.). Since search displays always contained both target colors participants had to keep track of the target color sequence. There were no cues indicating the upcoming target colors during a block, but participants received a reminder about the target color sequence and the first relevant target color in the first trial of the new block in the block breaks. The target color sequence (e.g., red/green or green/red) was randomized between participants but remained the same for each participant during the whole experiment. The locations of the two target color bars were determined randomly and independently of each other in each trial. The response-to-key mapping (vertical/horizontal response on arrow up/down key) and the hand-to-key mapping (left/right hand on arrow up/down key) was counterbalanced across participants but was kept constant for each participant for the duration of the whole experiment.

Probe displays that were presented prior to search (probes 1–7) or together with search (probe S) contained six items composed of four closely aligned dots, two on the vertical, and two on the horizontal axis (0.1°×0.1° for each dot, 0.25°×0.25° for each four-dot probe item). The probe items were also presented at the 1, 3, 5, 7, 9, and 11 o'clock positions of an imaginary circular clock face, but closer to fixation (at an eccentricity of 0.5°) than the search bars. One of the probe items was a color singleton that randomly matched one of the two possible target colors among five uniformly gray probe items. These gray probes were always equal in luminance to the color singleton probe (~11.9 cd/m$^2$). Probe singletons that matched the color of the upcoming search target were *relevant target color probes*, and probes that did not match this color but instead the other possible target color that was relevant before the last color switch were *irrelevant target color probes*. The probe singleton locations were selected randomly and independently in each probe display, with the following two restrictions: Successive singleton probes were equally likely to appear on same or opposite display sides, but immediate repetitions of the exact probe location (on the imaginary clock face) were not allowed. As a result, each probe display was equally likely to be preceded and followed by probe displays that contained a color singleton on the same or the opposite side. This was done to ensure that lateralized responses to any particular probe singleton would remain unaffected by any lateralised response triggered by singletons in temporally adjacent probe displays. Participants were informed that probe displays were task-irrelevant and could be ignored.

Experiment 1 contained 70 blocks of twelve trials each. Blocks were short to minimize the presence of

[1]A large effect size was expected to replicate partial eta squared values ($\eta_p^2$) of 0.14, which we measured in a previous RSPP experiment in which participants searched for two alternating target colors (3-way interaction between Laterality*Probe type*Probe number in Experiment 1 of Grubert & Eimer, 2020, p. 1531).

[2]In our previous work (e.g., Grubert & Eimer, 2018), probes that were presented together with the search displays (probe S) never triggered reliable N2pc components. However, these probes were still included in the present experiments to maintain a temporally consistent visual pattern of probe presentations throughout each block.

blinks within each block. In each block, the twelfth search display was followed by seven additional probe displays to keep stimulus conditions during the post-target response interval identical across all trials in a block. Each block thus contained twelve search displays and 91 probe displays (13 for each of the seven probes). The first trial in each block was excluded from all analyses, because it could not be classified as a target color repetition or switch trial. Each block therefore included six repetition and five switch trials. Before the experiment proper, participants practiced the task until they felt comfortable with it (usually after two to four blocks). These data were not recorded.

### 2.1.3 | EEG recording and data analyses

EEG was DC-recorded from 25 scalp sites (standard positions of the extended 10/20 system), sampled at 500 Hz, and digitally low-pass filtered at 40 Hz (no other filters were applied after data acquisition). Impedances were kept below 5 kΩ. The left earlobe served as online reference during data acquisition, but all channels were re-referenced offline to linked earlobes. The EEG was segmented into 500 ms time windows including a 100 ms pre-stimulus baseline and a 400 ms ERP time window following the onset of a particular stimulus display (probes 1 to 7, search display). Data from the first and last seven probe displays in each block, and from trials with anticipatory (<200 ms), very slow (>1500 ms), missing or incorrect responses were excluded from analysis. So were segments that contained eye movements (±30 μV in the bipolar HEOG channel), blinks (±60 μV at Fpz), and muscular movements (±80 μV in all channels). Artifact rejection resulted in an exclusion of 8.4% of all segments ($SD = 6.6\%$; ranging between 2.1% and 25.6% across participants). The remaining segments were averaged separately for each probe display (probes 1–7) in which the probes were in the left versus right hemifield. Separate averages were computed for relevant and irrelevant target color probes in target color repetition versus switch trials. In addition, averages were also computed for search displays with a target in the left or right hemifield.

N2pc components to probes were quantified based on ERP mean amplitudes obtained at lateral posterior electrodes PO7 and PO8, contralateral and ipsilateral to the side of a probe, within an 80 ms time window starting at 190 ms after the respective probe display onset. As in our previous work using analogous rapid serial probe presentation procedures (Grubert & Eimer, 2018), the start of this time window was determined by measuring the point in time (rounded to the nearest 10) when the ascending flank of the averaged probe N2pc (pooled across all relevant target color probes in Experiment 1) reached 50% of the peak amplitude (at −0.10 μV). N2pc components to target bars in the search displays were computed within the same 190–270 ms post-stimulus time window for consistency. Target N2pc onset latencies were substantiated by means of jackknife-based procedures (Miller et al., 1998). Eighteen grand-average difference waves (contralateral minus ipsilateral ERPs at PO7/8) were computed separately for targets in color repetition versus switch trials, each excluding one different participant from the original sample. N2pc onset latencies were defined as the point in time when each subsample difference wave reached an absolute onset criterion of −0.8 μV (50% of the peak amplitude of the pooled target N2pc in Experiment 1; see Grubert & Eimer, 2018, 2020, 2023, for identical procedures). All *t*-tests on jack-knifed N2pc onset latencies were power-corrected as suggested by Miller et al. (1998) and are denoted with $t_c$. Generally, all *t*-tests reported are two-tailed and Bonferroni and Greenhouse–Geisser corrected were 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 power corrected $t_c$-tests.

## 2.2 | Results

### 2.2.1 | Behavioral results

Trials with anticipatory (<200 ms) or exceedingly slow (>1500 ms) reaction times (RTs) were excluded from analysis (0.7% of all trials). Typical target color switch costs were observed both in RTs and error rates (see Figure 2, top panel). Mean RTs were 54 ms faster in target color repetition (629 ms) as compared to switch trials (683 ms), $t(17) = 5.8$, $p < .001$, $d = 0.67$, and error rates were 4.4% lower (6.5% vs. 10.8%), respectively, $t(17) = 6.1$, $p < .001$, $d = 0.95$.

### 2.2.2 | N2pc components for probe displays

To measure the time course of template activation prior to search, N2pcs elicited by probes that matched the relevant (upcoming) or the irrelevant (previous) target color were extracted by computing ERPs at posterior sites PO7/8, contralateral and ipsilateral to the side of a probe, separately for each of the seven successive probes in a trial (probes 1–7) in target color repetition versus switch trials. For illustration, these ERPs are shown in Figure 3 for relevant target color probes 1–7 in color repetition trials. ERPs for all other types of probes are included in the Supplementary Materials. The time course of the successive probe N2pcs is easier to see in Figures 4

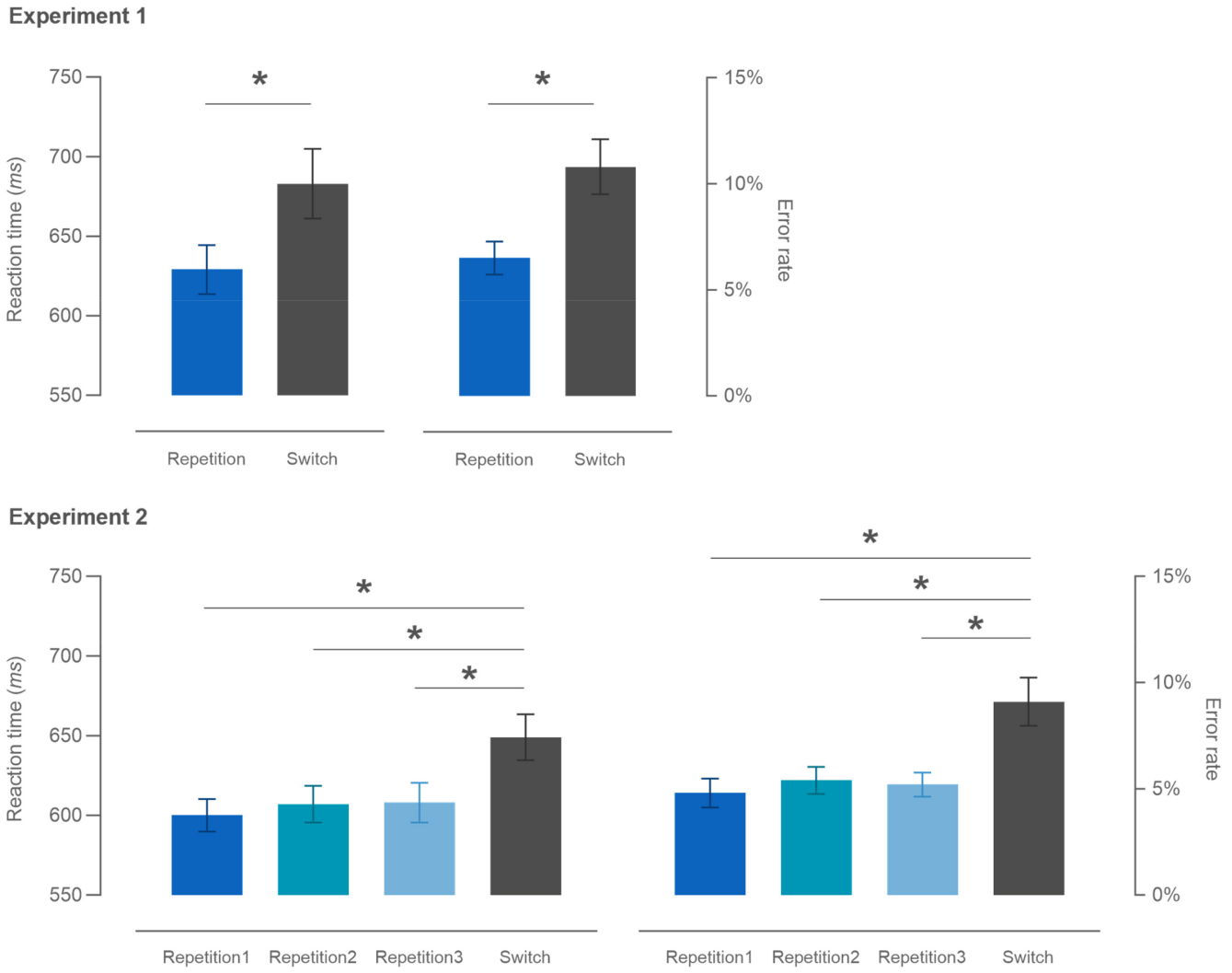


**FIGURE 2** Reaction times (measured in milliseconds; left axes) and error rates (percentage of all trials; right axes) measured in color repetition versus switch trials of Experiment 1 (top panel) and 1st, 2nd, and 3rd color repetition trials versus switch trials in Experiment 2 (bottom panel). Statistically reliable differences are marked by asterisks.

and 5 which show probe N2pc difference waves (obtained by subtracting ipsi- from contralateral ERPs at PO7/8) in a temporally continuous fashion, separately for relevant (Figure 4) and irrelevant (Figure 5) target color probes in color repetition (top panels) and switch trials (bottom panels), respectively. Note that N2pc components were extracted individually for each probe (probes 1–7) and that Figures 4 and 5 were compiled to show these probe N2pcs in a successive fashion for illustration purposes only. Each figure starts with the activity triggered in response to probe 1 (100 ms prior to 350 ms after onset of probe 1) which was the first probe presented directly after a previous search display. For the subsequent probes (probes 2–7), 200 ms intervals (150 to 350 ms after onset of each respective probe) are shown sequentially with interpolated data points between adjacent intervals. The onset of each probe is marked with a vertical line, and the N2pc time window for each probe (190–270 ms post-stimulus) is shaded in gray. As probes were presented every 200 ms, each individual probe was therefore presented within the N2pc time interval of its immediately preceding probe.

In line with our previous RSPP findings (Grubert & Eimer, 2018, 2020, 2023), Figure 4 (top panel) shows that relevant target color probes triggered N2pc components at intermediate and late stages during the search preparation period. These N2pcs were largest for probe 7, just before the next search display. Probes that were presented earlier in the trial did not trigger any N2pcs. Importantly, this pattern looked fundamentally different when relevant target color probes were presented in color switch trials (Figure 4, bottom panel). Here, only probe 7, which immediately preceded the search display, triggered an N2pc, whereas no clear N2pc was present for any of the preceding probes. Furthermore, irrelevant target color probes (Figure 5) never triggered any N2pcs,

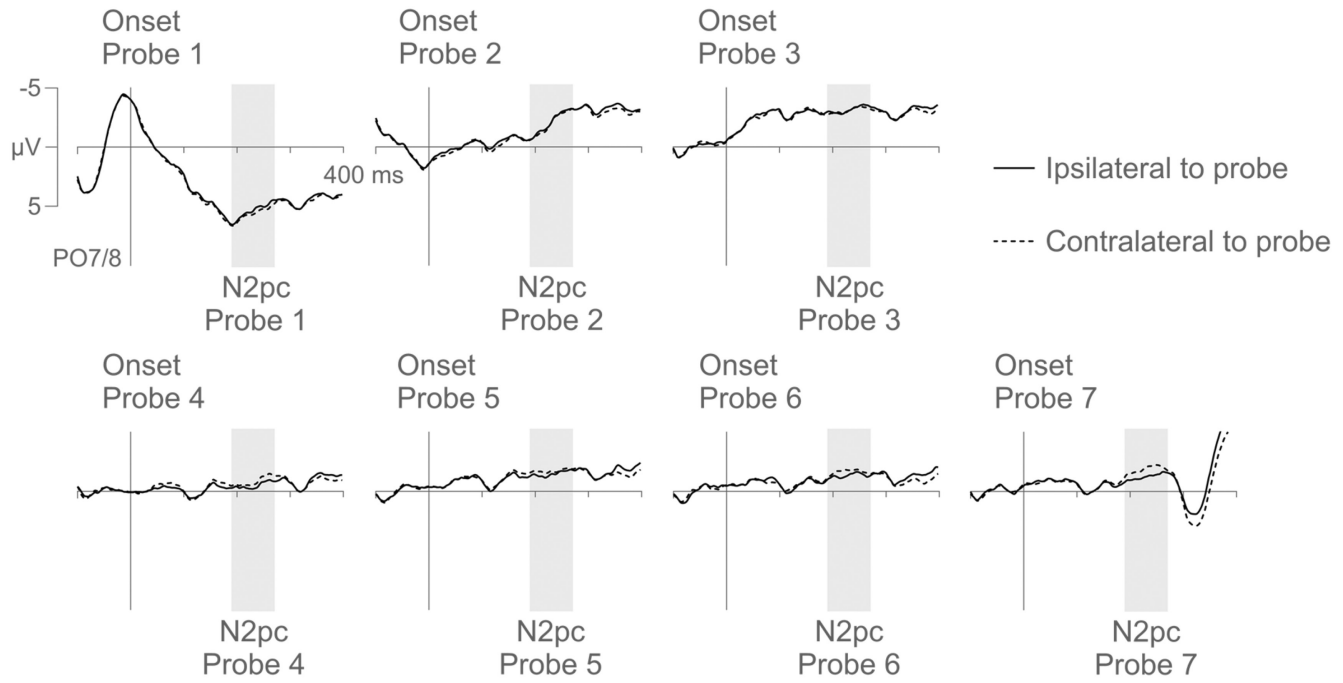


**FIGURE 3** Grand-averaged ERPs elicited by relevant target color probes in color repetition trials of Experiment 1 at electrodes PO7/8 contralateral and ipsilateral to color singleton probes in each of the seven probe displays presented between consecutive search displays. Probe 1 is the first probe to follow the previous search display and probe 7 is the probe to immediately precede the next search display. Shaded areas mark N2pc time windows (190–270 ms after onset of each individual probe).

neither in color repetition (top panel) nor switch trials (bottom panel).

Statistical analyses confirmed these informal observations. ERP mean amplitudes measured at PO7/8 in the 190–270 ms post probe time windows were fed into a repeated-measures omnibus ANOVA with the factors Trial Type (color repetition vs. switch), Probe Color (relevant vs. irrelevant target color probe), Probe Number (Probe 1, 2, 3, 4, 5, 6, 7), and Laterality (electrode contralateral vs. ipsilateral to the hemifield of a probe). The main effect of Laterality just failed to reach significance, $F(1,17)=3.6$, $p=.076$, $\eta_p^2=0.17$, but there was an interaction between Laterality and Probe Number, $F(6,102)=7.0$, $p<.001$, $\eta_p^2=0.29$, confirming that N2pc amplitudes differed between probes at different temporal positions. Laterality did interact with Trial Type and Probe Color, $F(1,17)=5.0$, $p=.039$, $\eta_p^2=0.23$, and there was also a significant four-way interaction, $F(7,98)=2.3$, $p=.034$, $\eta_p^2=0.14$. This suggests that the temporal pattern of probe N2pcs differed between relevant and irrelevant target color probes, and that this was further modulated by whether these probes were presented in color repetition or switch trials.

To assess differences between color repetition and switch trials more directly, two follow-up ANOVAs were conducted separately for relevant and irrelevant target color probes, with the factors Trial Type (color repetition vs. switch), Probe Number (Probe 1–7), and Laterality (contralateral vs. ipsilateral activity). For relevant target color probes, there was a main effect of Laterality, $F(1,17)=5.2$, $p=.036$, $\eta_p^2=0.23$, and an interaction between Laterality and Probe Number, $F(6,102)=10.6$, $p<.001$, $\eta_p^2=0.40$, confirming that probe N2pc amplitudes differed across the preparation period. Importantly, there was also a significant three-way interaction, $F(6,102)=2.3$, $p=.043$, $\eta_p^2=0.12$, indicating that the temporal pattern of probe N2pcs differed between target color repetition versus switch trials. This was confirmed by follow-up ANOVAs comparing ipsi-and contralateral activity in color repetition versus switch trials separately for each individual probe location. For probes 1, 2, and 3, there was no reliable contralateral negativity, all $F(1,17)<1$, $p>.452$, $\eta_p^2<0.03$, and no interactions involving the factor Laterality, all $F(1,17)<1.1$, $p>.327$, $\eta_p^2<0.06$, confirming that these early relevant target color probes did not trigger N2pcs, regardless of whether they were presented in color repetition or swich trials. In contrast, Laterality did interact with Trial Type for relevant target color probes 4, 5, and 6, all $F(1,17)>5.2$, $p<.037$, $\eta_p^2>0.23$. These probes produced reliable N2pc components only in color repetition trials (−0.34, −0.25, and −0.33 μV, respectively), all $t(17)>2.5$, $p<.021$, $d>0.27$, but not in color switch trials, all $t(17)<1$, $p>.471$, $d<0.01$. Finally, for probe 7, there was a main effect of Laterality, $F(1,17)=20.4$, $p<.001$, $\eta_p^2>0.55$, but no interaction with Trial Type, $F(1,17)<1$, $p=.969$, $\eta_p^2<0.01$. These probes triggered reliable N2pc components, both $t(17)>4.2$, $p=.001$, $d>0.58$, which were virtually identical

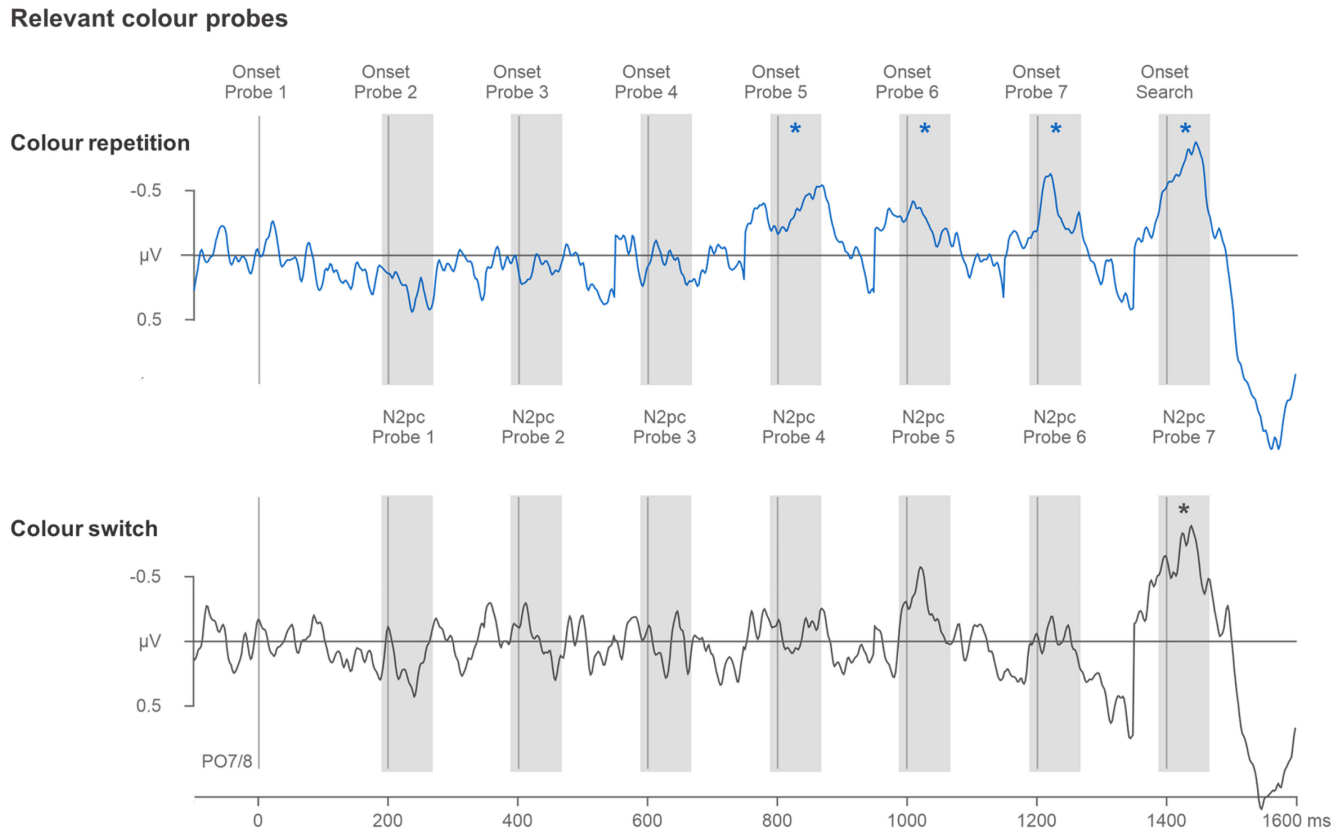


**FIGURE 4** N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for relevant target color probes in color repetition (top panel) and switch trials (bottom panels) of Experiment 1. Difference waves for the seven probes presented between search displays (probes 1–7) are shown in a temporally continuous fashion in 200 ms segments (150–350 ms) after onset of each probe. N2pc components were extracted individually for each probe, the successive presentation of the probe N2pcs is for illustration purposes only. Probe onsets are indicated by vertical lines, and probe N2pc time windows by shaded areas (190–270 ms after onset of each individual probe). Note that the onset of each probe coincides within the N2pc window for the preceding probe. Statistically reliable probe N2pcs are marked by asterisks.

in size (−0.63 µV), $t(17) < 1$, $p > .969$, $d < 0.01$, irrespective of whether they were presented in color repetition or switch trials.

The ANOVA for irrelevant target color probes did not produce any reliable main effects or interactions involving the factor Laterality, all $F(1,17) < 2.0$, $p > .084$, $\eta_p^2 < 0.10$, confirming that none of these probes triggered an N2pc, regardless of whether they were presented in color repetition or switch trials.

### 2.2.3 | N2pc components in the search displays

N2pcs elicited by search targets in color repetition versus switch trials were measured at PO7/8 in the 190–270 ms time window after search display onset. These ERPs, together with the respective N2pc difference waves, are shown in Figure 6 (top panel). A repeated-measures ANOVA with the factors Trial Type (color repetition vs. switch) and Laterality (contralateral vs. ipsilateral activity) revealed a main effect of Laterality, $F(1,17) = 41.4$, $p < .001$, $\eta_p^2 = 0.71$, and a significant interaction, $F(1,17) = 12.9$, $p = .002$, $\eta_p^2 = 0.43$, demonstrating that reliable target N2pcs were triggered both in repeat and switch trials, both $t(17) > 4.6$, $p < .001$, $d > 0.24$, but that N2pc amplitudes were larger in color repetition trials (−1.2 vs. −0.8 µV, respectively). Matching the behavioral RT pattern, the N2pc also emerged earlier in color repetition as compared to color switch trials (204 vs. 231 ms), $t_c(17) = 2.9$, $p = .012$, $\eta_p^2 = 0.42$.[3]

## 2.3 | Discussion of Experiment 1

As expected, search performance was impaired on target switch as compared to target repeat trials, with slower

[3]The same jack-knifed onset latency analysis was also conducted with a relative onset criterion (50% of each subsample's peak amplitude, as recommended by Kiesel et al., 2008). Results were identical: Target N2pcs were faster in color repetition (206 ms) than switch trials (228 ms), $t_c(17) = 2.3$, $p = .040$, $\eta_p^2 = 0.31$.

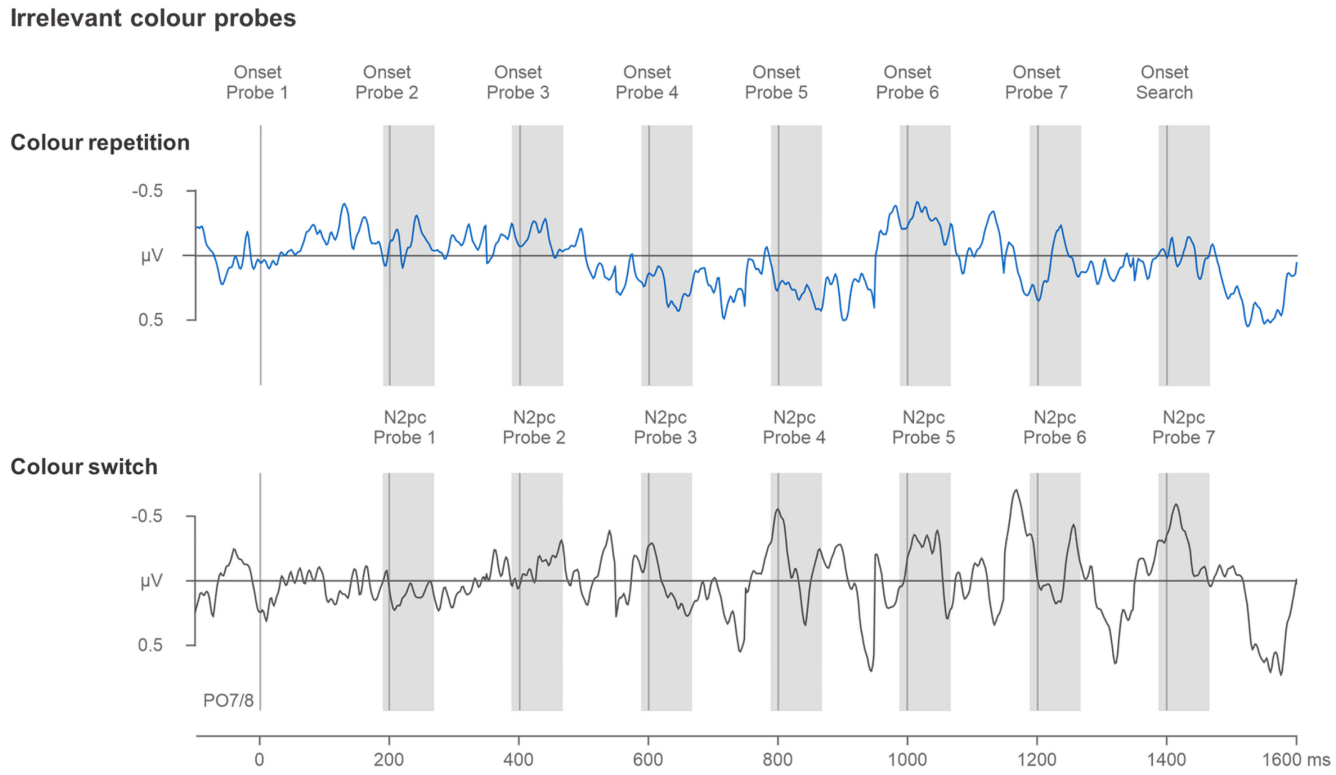


**FIGURE 5** N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for irrelevant target color probes in color repetition (top panel) and switch trials (bottom panels) of Experiment 1. Difference waves triggered by individual probes are shown in the same continuous fashion as in Figure 4. Probe onsets are indicated by vertical lines, and probe N2pc time windows by shaded areas (190–270 ms after onset of each individual probe). None of these probes triggered reliable N2pcs.

RTs and higher error rates. The presence of such target switch costs is analogous to the costs observed for predictable changes of stimulus–response mappings (e.g., Rogers & Monsell, 1995). They also mirror the target switch costs observed in previous visual search tasks (e.g., Grubert & Eimer, 2013; Olivers & Meeter, 2006), and demonstrate that such costs occur even when a change of target identity is fully predictable. Notably, these behavioral costs were accompanied by corresponding modulations of N2pc components triggered by search targets on switch versus repeat trials. These N2pcs were smaller and emerged significantly later on switch trials, indicating that the allocation of attention to target objects was slower and less efficient on these trials.

The critical new finding of Experiment 1 concerned the temporal pattern of probe N2pc components observed prior to switch or repeat trials, which revealed clear switch-induced costs for the preparatory activation of target color templates. On target repeat trials, this template was active from about 800 ms prior to search display onset, as reflected by the presence of reliable N2pc components to singleton probes that matched this target color from probe 4 onwards. On target switch trials, the activation of the template for the new target color was considerably delayed. Here, a reliable N2pc was only present for the target color probe that immediately preceded the search display, but not for any earlier probe. This difference suggests that the need to change a color-specific target template across successive trials delays the point in time at which this template is activated during search preparation.

This delay could in principle be caused by task-set inertia on switch trials, as the continued persistence of the previously relevant target template may interfere with the activation of a new template. However, the N2pc results of Experiment 1 provide no evidence for this hypothesis. Any continued activation of the target template for the currently irrelevant target color should have been reflected by reliable N2pc components triggered by the corresponding color singleton probe during the preparation period, in particular on switch trials. However, N2pcs for irrelevant target color probes were entirely absent, not only on repeat but also on switch trials. Thus, there was no evidence that any task-set inertia across successive trials might have contributed to the observed switch costs.

The absence of any N2pcs for irrelevant target color probes may seem surprising, given that our previous experiment which employed an ABAB design (Grubert & Eimer, 2020) observed clear N2pcs for probes that matched

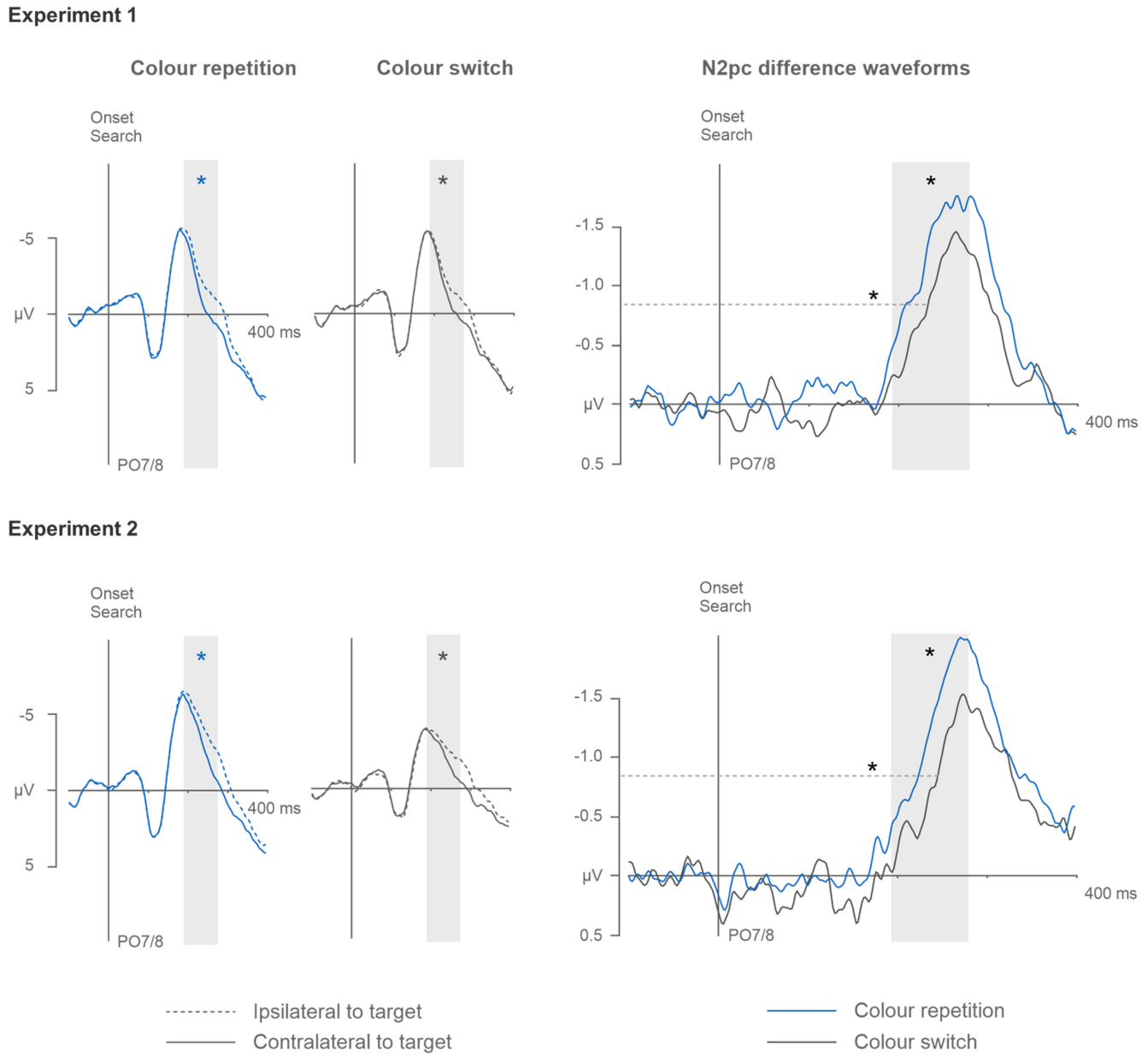


**FIGURE 6** Grand-averaged ERPs elicited in the search displays in color repetition and switch trials of Experiment 1 (top panel) and Experiment 2 (bottom panel) at electrodes PO7/8 contralateral and ipsilateral to the response-relevant target (left panels), together with the corresponding contralateral-ipsilateral N2pc difference waveforms (right panel). In Experiment 2, to equate the signal-to-noise ratio between the two trial types, only 1st color repetition trials were included in the target N2pc analyses. Shaded areas indicate N2pc time windows (190–270 ms after search display onset). Asterisks in the ipsi/contralateral panels (left) indicate significant N2pcs. Asterisks in the difference wave panels (right) represent significant differences in mean amplitudes and onset latencies (measured at −0.8 μV, as indicated by the dashed horizontal lines).

either the preceding or the upcoming target color, indicating that both color templates (including the template that was not relevant for the next search episode) were activated in parallel. Given this apparent discrepancy (which will be further considered in the General Discussion), it is important that the results of Experiment 1 are replicated before any firm conclusions about the factors responsible for search target switch costs can be drawn.

One goal of Experiment 2 was to provide such a replication. The other goal was to investigate the impact of the number of task repetitions on the activation of target templates and the possible emergence of task-set inertia. The task setup and experimental logic were the same as in Experiment 1, except that the length of each alternating run with the same search target color was increased from two to four (i.e., AAAABBBB). As noted before,

Monsell et al. (2003) employed an analogous manipulation and found behavioral switch costs only for the first trial after a switch, suggesting that task sets are fully established after a new task has been performed once. In Experiment 2, we investigated whether this also applies to switches between templates for target features.

To confirm the main results of Experiment 1, we first compared N2pc components triggered by relevant target color probes on switch trials and on first color repetition trials that immediately followed the target color switch. The central question was whether the delay of preparatory target template activation on switch trials (as reflected by the later emergence of probe N2pcs) found in Experiment 1 would also be observed in Experiment 2.

The four-trial alternating runs procedure in Experiment 2 made it possible to investigate whether task-set inertia in target template activation might emerge when the previous template remained continuously relevant across multiple trials. If this was the case, evidence for inertia (i.e., reliable probe N2pcs for irrelevant target color probes) might be observed for target switch trials in Experiment 2, as these trials where always preceded by four (as compared to two) trials where this color was relevant. Furthermore, increasing the number of target color repetitions might also differentially affect the activation of target color templates across successive repeat trials. To test this, we compared the temporal pattern of target color probe N2pcs elicited prior to the first, second, and third color repetition of a particular search target.

# 3 | EXPERIMENT 2

## 3.1 | Methods

### 3.1.1 | Participants

Nineteen new participants were paid to participate in Experiment 2. All participant procedures were identical to Experiment 1. One participant was excluded due to excessive eye movement activity (>40% trials lost during artifact rejection). The remaining 18 participants were between 18 and 47 years of age (mean = 27.5, $SD = 7.5$). Fourteen participants were female and four were male. One participant was left-handed, the remaining 17 participants were right-handed. All participants had normal or corrected-to-normal vision and normal color vision (as tested with Ishihara, 1972).

### 3.1.2 | Stimuli and procedures

All experimental procedures were identical to Experiment 1 with the following exceptions: Each block now contained 16 trials and the response-relevant target color switched after every fourth trial (e.g., red in trials 1–4, green in trials 5–8, red in trials 8–12, green in trials 13–16). Search displays contained both the relevant and irrelevant target color bar together with four differently colored nontarget bars of the color set, as described in Experiment 1. As in Experiment 1, probes 1–7 and probes S were randomly shown in either of the two target colors and were either relevant target color probes (that matched the upcoming target color) or irrelevant target color probes (that matched the previous target color that was relevant before the last color switch). Experiment 2 contained 64 blocks of 16 trials each. The sixteenth search display was followed by seven additional probe displays for constant response conditions, so that each block contained 16 search displays and 119 probe displays (17 for each of the seven probs).

### 3.1.3 | EEG recording and data analyses

All EEG procedures were identical to Experiment 1. During artifact rejection, 3.3% of all segments were excluded from analysis in Experiment 2 ($SD = 2.3\%$; ranging between 0.9% and 9.4% across participants). Averaged ERP waveforms were computed for probes 1–7 in the left or right hemifield, separately for relevant and irrelevant target color probes. Separate averages were computed for color switch trials (i.e., the first trial with a new target color after four successive trials with the other target color), and for the 1st, 2nd, and 3rd color repetition trial before a target color switch. Apart from allowing the assessment of possible effects of successive target color repetitions on target template activation, this also kept the signal-to-noise ratio equivalent across all types of trials. All data analysis procedures were identical to Experiment 1. In addition, Bayesian statistics (Rouder et al., 2009) were used in JASP to evaluate empirical evidence in favor of the null hypothesis. Substantial evidence for the null hypothesis is marked by Bayes factors ($BF_{01}$) > 3 (Jeffreys, 1961), indicating that the empirical data are more than three times more likely under the null hypothesis as compared to the alternative hypothesis.

## 3.2 | Results

### 3.2.1 | Behavioral results

After exclusion of all trials with anticipatory or slow responses (0.6% of all trials), RTs in correct trials and error rates were subjected to two repeated measures ANOVAs

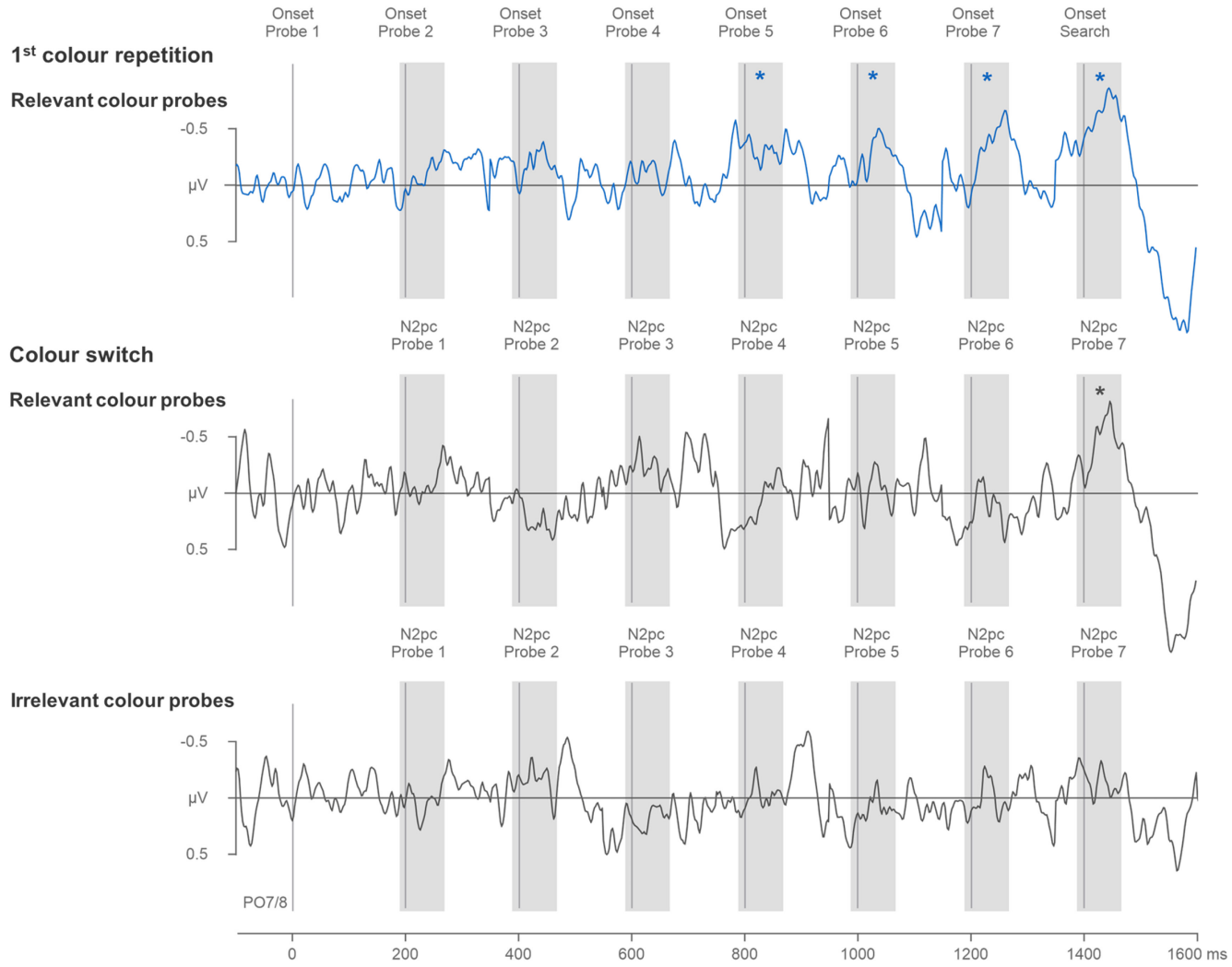


**FIGURE 7** N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for relevant target color probes in 1st color repetition trials (top panel) and in switch trials (middle panel), and for irrelevant target color probes in switch trials (bottom panel) of Experiment 2. Difference waves triggered by individual probes are shown in the same continuous fashion as in Figures 4 and 5. Probe onsets are indicated by vertical lines, and probe N2pc time windows by shaded areas (190–270 ms after onset of each individual probe). Statistically reliable probe N2pcs are marked by asterisks.

with the factor trial type (1st color repetition, 2nd color repetition, 3rd color repetition, vs. color switch). Both ANOVAs revealed main effects, both $F(3,51) > 14.8$, $p < .001$, $\eta_p^2 > 0.46$, indicating that RTs and error rates differed between these four types of trials. As can be seen in Figure 2 (bottom panel), RTs were slower and errors more frequent in color switch trials (RT: 649 ms; error rate: 9.1%) relative to trials where the target color was repeated for the first, second or third time (RTs: 600, 607, and 608 ms; error rates: 4.8%, 5.4%, and 5.2%). Follow-up t-tests confirmed that the corresponding RT and error rate differences were significant, all $t(17) > 4.0$, $p < .007$, $d = 0.95$. In contrast, there were no further benefits for performance when the same target color was repeated for the second or third time. RTs and error rates were numerically even higher for these trials relative to 1st color repetition trials, but these differences were not reliable, all $t(17) < 2.2$, $p > .222$, $d < 0.15$.

### 3.2.2 | N2pc components for probe displays

Figure 7 shows probe N2pc difference waves (obtained by subtracting ipsi- from contralateral ERPs at PO7/8) in the same temporally continuous fashion as in Figures 4 and 5. The top and middle panel show N2pcs in response to relevant target color probes in 1st target color repetition and switch trials, respectively. The temporal pattern of probe N2pcs in these two types of trials was identical to the results observed in Experiment 1, with clear N2pcs emerging from probe 4 onwards on repetition trials, but only for probe 7 on switch trials. For relevant target color probes

1–3, there was no main effect or interactions involving the factor Laterality, all $F(1,17)<1$, $p>.361$, $\eta_p^2<0.05$, demonstrating that these early probes did not trigger any N2pcs. An ANOVA conducted for probes 4–6 produced a main effect of Laterality, $F(1,17)=7.2$, $p=.016$, $\eta_p^2=0.30$, but importantly, also a significant interaction between Trial Type and Laterality, $F(1,17)=6.1$, $p=.024$, $\eta_p^2=0.27$. Follow-up comparisons confirmed that relevant target color probes 4, 5, and 6 produced reliable N2pcs in 1st color repetition trials (−0.3, −0.3, and −0.5 μV, respectively), all $t(17)>2.2$, $p<.041$, $d>0.10$, but not in color switch trials, all $t(17)<1$, $p>.418$, $d<0.01$. In contrast, and as in Experiment 1, relevant target color probes 7 triggered reliable N2pcs both in color repetition (−0.6 μV) and switch trials (−0.5 μV), both $t(17)>2.7$, $p>.014$, $d>0.32$, which did not differ from each other, $t(17)<1$, $p>.375$, $d<0.01$.

To assess the existence of target template inertia effects on switch trials after the same color template had been involved in search preparation and target selection in four successive trials, we analyzed N2pcs to irrelevant target color probes on these trials (as shown in Figure 7, bottom panel). A repeated-measures ANOVA with the factors Probe Number (1–7) and Laterality, did not produce a main effect of Laterality, $F(1,17)<1$, $p=.944$, $\eta_p^2<0.01$, and also no interaction involving the factor Laterality, $F(6,102)<1$, $p=.746$, $\eta_p^2=0.03$. In other words, there was no evidence for any residual activation of the corresponding color template, even though this template had been activated in the four preceding trials.[4] Further support for the null hypothesis was provided by the corresponding Bayes factors for both the main effect, $BF_{01}=4.9$, and interaction, $BF_{01}=20.0$.

Finally, we also analyzed possible effects of successive target color repetitions on the activation of the corresponding relevant color template. ERPs in response to relevant target color probes in 1st, 2nd, and 3rd color repetition trials were analyzed in a repeated-measures ANOVA with the factors Trial Type (1st, 2nd, 3rd color repetition), Probe Number (probe 1–7), and Laterality. Both the main effect of Laterality, $F(1,17)=5.4$, $p=.033$, $\eta_p^2=0.24$, and the interaction between Probe Number and Laterality reached significance, $F(6,102)=4.3$, $p=.001$, $\eta_p^2=0.20$, reflecting the absence of N2pcs for early probes (see above). However, and importantly, Trial Type did not interact with Probe Number and Laterality, $F(1,17)<1$, $p=.965$, $\eta_p^2=0.02$, $BF_{01}=172.2$, demonstrating that successive repetitions of the same target color did not affect the temporal pattern probe N2pcs during search preparation. The continuous N2pc difference waves in response to relevant target color probes on 2nd and 3rd color repetition trials are included in the Supplementary Materials.

### 3.2.3 | N2pc components in the search displays

Target N2pcs in color repetition versus switch trials are shown in Figure 6 (bottom panel). To equate the signal-to-noise ratio between the two trial types, only 1st color repetition trials were included in the target N2pc analyses. A repeated-measures ANOVA with the factors Trial Type (1st color repetition vs. switch) and Laterality (contralateral vs. ipsilateral activity) revealed a main effect of Laterality, $F(1,17)=32.93$, $p<.001$, $\eta_p^2=0.66$, and a significant interaction, $F(1,17)=12.2$, $p=.003$, $\eta_p^2=0.42$. Substantial N2pcs were triggered both in color repetition and switch trials, both $t(17)>4.1$, $p<.002$, $d>0.33$, but N2pcs triggered in color repetition than switch trials were larger (−1.1 vs. −0.6 μV, respectively). N2pcs in color repetition as compared to switch trials were also triggered earlier (218 vs. 245 ms), $t_c(17)=4.1$, $p=.001$, $\eta_p^2=0.59$.[5]

## 3.3 | Discussion of Experiment 2

The results of Experiment 2 were clear-cut. First, and most importantly, the pattern of probe N2pc components observed on target color switch and repetition trials fully confirmed the results of Experiment 1. Again, probe N2pcs were reliably present on switch trials only for the probe display that immediately preceded the search display. In contrast, they emerged from probe 4 onwards on the first repeat trial following a target switch. Behaviorally, there were again clear behavioral performance costs on target switch relative to target repeat trials, and these costs were again mirrored by smaller and delayed target N2pc components on switch trials. Notably, there were no further performance improvements for the second and third repetition of a given target color relative to its first repetition. This is in line with the results found by Monsell et al. (2003) for successive repetitions of S-R mappings, and suggests that analogous to such mappings, target templates are also fully activated after they have been used once to guide target selection. Further support for this conclusion comes from the comparison of probe N2pcs on successive target color repetition trials in Experiment 2, which found no difference in preparatory template

[4]As would be expected, there were also no N2pcs for irrelevant target color probes on 1st, 2nd, and 3rd target color repetition trials, i.e., no increased contralaterality at PO7/8 and no interactions involving the factor laterality, all $F<1$, $p>.336$, $\eta_p^2<0.06$. The corresponding continuous probe N2pc difference waveforms for these trials are included in the Supplementary Materials, for completeness.

[5]The same latency analysis with a relative 50% onset criterion also revealed faster target N2pcs in color repetition (228 ms) than switch trials (242 ms), $t_c(17)=2.4$, $p=.028$, $\eta_p^2=0.34$.

activation prior to the first, second, and third repetition of a particular target.

Finally, Experiment 2 obtained no evidence for any task-set inertia effects for target template activation processes on switch trials. Even though the previous target color had been relevant on four successive trials, there was no indication that the corresponding color template was partially activated on switch trials. Analogous to Experiment 1, there were no N2pc components in response to irrelevant target color probes at any point during the preparation period, indicating that these probes failed to attract attention throughout this interval.

## 4 | GENERAL DISCUSSION

The goal of the present study was to provide new insights into the mechanisms involved in switching target templates in visual search. In tasks where observers search for one of several possible target objects, performance may be impaired on trials where the identity of the target changes relative to target repeat trials, even when the identity of the next target is fully predictable. Such search target switch costs might be similar to the behavioral task switch costs observed in many previous experiments (e.g., Monsell, 2003), in that they are produced, at least in part, by processes that operate during the preparation for an upcoming task. Preparatory target template activation processes might differ between target switch and target repeat trials, and this could result in performance costs, analogous to the task-set reconfiguration mechanisms investigated in previous research on task switching (e.g., Rogers & Monsell, 1995).

To compare and contrast preparatory target template activation processes on target switch and repeat trials, we employed the alternating runs procedure introduced by Rogers and Monsell (1995). Participants searched for targets that were defined by one of two possible colors, which changed predictably on every second trial (Experiment 1) or every fourth trial (Experiment 2). To track target template activation in real time, N2pc components were recorded in response to brief probe displays which appeared in rapid succession between search displays, and contained a color singleton item that either matched the upcoming target color or the other currently irrelevant color.

Similar to our previous studies that employed analogous RSPP procedures (Grubert & Eimer, 2018, 2020, 2023), probes that matched the fully predictable upcoming target color triggered N2pc components when they appeared during the 800 ms interval prior to the arrival of the next search display. This temporal pattern was observed prior to target color repetition trials. It demonstrates that these probes attracted attention, and that a corresponding color-specific target template was active at the moment when they were presented. This is in line with previous experiments where observers always searched for a single color-defined target (e.g., Grubert & Eimer, 2018) and shows that target templates are activated in a transient fashion during the preparation for each new search episode. The critical new finding of the present study was that the emergence of probe N2pc components was strongly delayed prior to target color switch trials. Here, an N2pc was only observed for the final probe display that appeared 200 ms prior to search display onset, but not in response to any of the preceding probes. This temporal dissociation in the pattern of probe N2pcs between target color switch and repetition trials was observed in Experiment 1 and was replicated in Experiment 2, where the length of alternating runs was increased from two to four trials.

The marked difference in the temporal pattern of target color probe N2pcs elicited prior to the onset of the next search display on target color switch versus repetition trials strongly suggests that target templates are activated at a later point in time during the preparation for a target switch trial relative to a target repeat trial. The delayed emergence of target color probe N2pcs on color switch trials might reflect the time demands of target template reconfiguration processes, analogous to the task-set reconfiguration processes studied by Rogers and Monsell (1995). There were also clear behavioral target switch costs in both experiments, for RTs as well as error rates (see also Grubert & Eimer, 2013; Olivers & Meeter, 2006, for similar observations), in spite of the fact that the identity of the next target was fully predictable on all trials, and sufficient time was available between search displays to activate a corresponding target color template. The delay of N2pc components to target color probes on switch as compared to repetition trials observed in both experiments (about 600 ms) was considerably larger than the switch costs for RTs (about 50 ms) and target N2pc onset latencies (25–30 ms). This delay was also larger than the template switch times estimated by Dombrowe et al. (2011) in an eye tracking study on the basis of saccade accuracy and latency on target color switch versus repetition trials (about 250 ms). These differences suggest that task switching has substantially stronger effects on the time course of preparatory search template activation than on the timing of subsequent attentional guidance and target selection processes.

In spite of differences in their magnitude, it is plausible to assume that behavioral target color switch costs are at least in part the result of temporal template switch costs (i.e., delayed activation of target templates on

switch trials) during the search preparation period. Alternatively, both these costs could also have been produced by a form of task-set inertia (e.g., Allport & Wylie, 1999), that is, a competition between the currently relevant target color template and the residual activation of the previously relevant color template. Such template inertia effects will be reflected by the presence of N2pc components to singleton probes that match the irrelevant target color. These N2pcs should have been observed specifically on target switch trials, indicating that the corresponding color template remained partially activated on these trials. However, no evidence for the presence of any target template inertia was found in either experiment. Singleton probes that matched the currently irrelevant target color did not trigger N2pc components on switch trials at any point during the preparation interval. This was the case in Experiment 1 for switch trials that followed two repetitions of the other target color, and in Experiment 2 after four repetitions of the other target color. These observations strongly suggest that target template activation processes were color-selective throughout, without any residual template inertia on target switch trials.[6] Thus, the presence of performance costs and the delay of target color probe N2pcs on these trials cannot be attributed to any residual activation of previously relevant color templates. In other words, search templates were switched off rapidly and fully during the preparation period of switch trials (see also Grubert et al., 2017; Olivers & Eimer, 2011, for additional electrophysiological and behavioral evidence for a fast de-activation of target templates that are no longer relevant).

The complete absence of N2pc components to irrelevant target color probes in the current study may seem surprising, given that a previous study (Grubert & Eimer, 2020) obtained clear evidence for the parallel activation of two color templates during search preparation. In this earlier study, two target colors alternated across successive trials, and probes that matched the previous or the upcoming target color both triggered reliable N2pcs during the preparation period. In contrast to this study, where all trials were effectively target switch trials, the current experiments used an alternating runs procedure with predictable target switch and repeat trials. This difference may have resulted in observers adopting different search preparation strategies. Both target templates may have been activated concurrently when target colors swapped between consecutive trials, whereas only the relevant target color template may be activated during search preparation when search targets always repeat at least once. It is interesting to note that observers chose to activate only the current target template in the current study, even though this single-template strategy resulted in sizeable behavioral costs on target switch trials. It is possible that maintaining a single template is less demanding than the co-activation of two templates, and/or that any performance costs on switch trials are compensated for by substantial benefits on target color repetition trials. The availability of different target template activation strategies, the factors that determine which strategy will be adopted in a particular task context, and the behavioral consequences of these choices, need to be investigated systematically in future research.

A crucial question posed by the present results concerns the relationship between the target template switch costs observed during the preparation for search and the target switch costs found for search performance. The temporal pattern of relevant target color probe N2pcs observed in both experiments shows that preparatory target templates are activated earlier on color repetition as compared to switch trials. However, these templates appeared to have been activated equally strongly on color repetition and switch trials immediately prior to the presentation of the next search display, as reflected by the absence of any amplitude differences of the N2pc to probe 7. If target templates were equally active on all trials at the moment a search display was presented, it would be reasonable to assume that there should be no systematic difference in their ability to guide attention towards target locations. In fact, the pattern of target N2pc components suggested that this was not the case, and that search guidance was more effective on repeat trials. In both experiments, target N2pcs were smaller and emerged significantly later on color switch as compared to repetition trials, indicative of target switch costs at the level of template-guided attentional target selection. These observations suggest that the quality of search guidance may not be exclusively determined by the activation state of a target template when the search display is presented but is also affected by the temporal profile of template activation processes. Guidance appears to be more effective when the relevant target color template has been activated earlier.

It should also be noted that the preparation for search does not just involve the activation of templates for target-defining features such as color, but also the activation of templates for response-relevant features (e.g., target orientation, as in the present study). Observers are only fully

[6]The absence of any N2pcs to singleton probes that matched the currently irrelevant target color also demonstrates that probe N2pc components were not associated with any salience-driven exogenous attentional capture triggered by color singletons in probe displays (see also Grubert & Eimer, 2018, 2023, for further demonstrations that distractor-color singleton probes do not trigger N2pcs).

prepared for an upcoming search task when both a template for the guidance of search and a template for target discrimination and response selection are activated (see Wolfe, 2023, for a similar distinction between guiding and target templates). Preparatory guidance templates may generally be activated prior to target templates because they are required for the guidance of attention at an early stage of the upcoming search process. If this is the case, the delayed activation of guidance templates observed in the current study on switch trials may be accompanied by an even later activation of target templates. This could result in costs for target identification and response selection on switch relative to repeat trials. In short, switch-related delays of preparatory target template activation processes could affect both the guidance of attention and the subsequent processing of target objects, and behavioral target switch costs could be generated at either or both of these stages.

In summary, the current study obtained new insights into the mechanisms involved in the preparatory activation of search target templates and the switch between templates across successive trials. Using on-line electrophysiological markers of target template activation, we demonstrated strong temporal template switch costs during search preparation, reflected by considerable delays in the activation of target color templates on switch trials. In contrast, there was no evidence that any target template inertia on switch trials could have contributed to the target switch costs observed for search performance. We suggest that the delay in the activation of target templates on switch trials can adversely affect early attentional guidance mechanisms as well as subsequent target identification and response selection processes.

## AUTHOR CONTRIBUTIONS

**Anna Grubert:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; writing – original draft; writing – review and editing. **Ziyi Wang:** Data curation; visualization; writing – review and editing. **Martin Eimer:** Conceptualization; funding acquisition; investigation; methodology; writing – original draft; writing – review and editing.

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## CONFLICT OF INTEREST STATEMENT

None.

## DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available upon request.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**Figure S1.** Grand-averaged ERPs elicited in Experiment 1 at electrodes PO7/8 contralateral and ipsilateral to each of the seven color singleton probes presented between consecutive search displays. ERPs are shown separately for relevant target color probes in color switch trials (top panel; see Figure 3 for the corresponding ERPs in color repetition trials) and for irrelevant target color probes in color repetition and switch trials (bottom panels). N2pc

time windows are indicated by shaded areas (190–270 ms after onset of each individual probe).

**Figure S2.** Grand-averaged ERPs elicited in Experiment 2 at electrodes PO7/8 contralateral and ipsilateral to each of the seven color singleton probes presented between consecutive search displays. ERPs are shown separately for relevant target color probes in 1st color switch trials (top panel) and for relevant and irrelevant target color probes in color switch trials (bottom panels). N2pc time windows are indicated by shaded areas (190–270 ms after onset of each individual probe).

**Figure S3.** N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for relevant target color probes in 2nd (top panel) and 3rd color repetition trials (bottom panel) of Experiment 2 (the corresponding difference waves for 1st color repetition trails can be seen in Figure 7). Difference waves triggered by individual probes are shown in the same continuous fashion as in Figures 4 and 5. Probe onsets are indicated by vertical lines, and probe N2pc time windows by shaded areas (190–270 ms after onset of each individual probe). Statistically reliable probe N2pcs are marked by asterisks.

**Figure S4.** N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for irrelevant target color probes in all types of color repetition trials of Experiment 2. Probe onsets are indicated by vertical lines, and probe N2pc time windows by shaded areas (190–270 ms after onset of each individual probe).

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