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The control of single-colour and multiple-colour visual search by attentional templates in working memory and in long-term memory

Anna Grubert¹, Nancy Carlisle², and Martin Eimer¹

¹Department of Psychological Sciences, Birkbeck, University of London

²Department of Psychology, Lehigh University

Correspondence concerning this article should be addressed to Anna Grubert, Department of Psychological Sciences, Birkbeck, University of London, Malet Street, London WC1E 7HX, UK. E-mail: a.grubert@bbk.ac.uk

Abstract

The question whether target selection in visual search can be effectively controlled by simultaneous attentional templates for multiple features is still under dispute. We investigated whether multiple-colour attentional guidance is possible when target colours remain constant and can thus be represented in long-term memory but not when they change frequently and have to be held in working memory. Participants searched for one, two, or three possible target colours that were specified by cue displays at the start of each trial. In constant-colour blocks, the same colours remained task-relevant throughout. In variable-colour blocks, target colours changed between trials. The contralateral delay activity (CDA) to cue displays increased in amplitude as a function of colour memory load in variable-colour blocks, which indicates that cued target colours were held in working memory. In constant-colour blocks, the CDA was much smaller, suggesting that colour representations were primarily stored in long-term memory. N2pc components to targets were measured as a marker of attentional target selection. Target N2pc were attenuated and delayed during multiple-colour search, demonstrating less efficient attentional deployment to colour-defined target objects relative to single-colour search. Importantly, these costs were the same in constant-colour and variable-colour blocks. These results demonstrate that attentional guidance by multiple-feature as compared to single-feature templates is less efficient both when target features remain constant and can be represented in long-term memory, and when they change across trials and therefore have to be maintained in working memory.

Introduction

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

Because visual WM can typically hold three or four objects simultaneously (e.g., Cowan, 2001; Vogel, Woodman, & Luck, 2001), it would seem reasonable to assume that multiple attentional templates may be concurrently active during visual search. If several search templates can operate in parallel, template-guided search for different possible target objects or features should be similarly effective as search for one specific object/feature. However, there is substantial evidence that this is not the case. For example, Houtkamp and Roelfsema (2009) demonstrated that target detection in rapid serial visual presentation (RSVP) tasks is impaired when observers search for two possible objects relative to single-object search. According to these authors, these impairments reflect the fact that only one attentional template for a particular target object can be active at any moment in time. Analogous capacity limitations of template-guided attention have been observed during visual search for simple visual features, such as colour. Targets that are defined by a one specific colour are usually found rapidly, whereas the detection of colour conjunction targets (e.g., red/blue targets among blue/green and red/green distractors) is inefficient (Wolfe et al., 1990). Again, this suggests that search can be guided by only one attentional template for one specific target colour at a time (e.g., Wolfe, 2007). Along similar lines, Dombrowe, Donk, and Olivers (2011) found that sequential eye movements to two colour-defined targets are slower and more error-prone when these targets differ in their colour than when their colour is identical, thereby demonstrating the difficulty of maintaining two colour-specific attentional sets. Analogous evidence for impaired search

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

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

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

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

presented among a variable number of distractors in different nontarget colours. While reaction times increased with increasing display set size, the onset latency of target N2pc components remained unaffected by set size, again suggesting efficient attentional target selection during multiple-colour search.

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

2011). In these constant-shape blocks, CDA amplitudes decreased in size across the first few trials, indicating that this transfer of search templates to long-term storage takes place rapidly (see Gunseli, Olivers, & Meeter, 2014, for evidence that this CDA decrease can be observed both for easy and difficult search tasks).

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

To confirm that target templates in constant-colour blocks were less likely to rely on working memory than in variable-colour blocks, we recorded CDA components during the

interval between cue and search displays at posterior electrodes contralateral to the side of the currently task-relevant items in the cue displays. In line with the findings of Carlisle et al. (2011), CDA components were expected to emerge in variable-colour blocks, and to increase in amplitude as a function of colour load. If attentional templates are no longer held in working memory when target features remain unchanged across blocks of trials, no CDA components should be found at all in constant-colour blocks. To assess our main research question regarding the speed and efficiency with which focal attention was deployed to target objects in the subsequent search displays, we measured N2pc components elicited in response to these targets. If multiple colour-specific attentional templates can be activated simultaneously when target colours remain constant but not when these colours vary across trials, target N2pc components should differ between constant-colour and variable-colour blocks during multiple-colour search (Two and Three Colour tasks). N2pc components should be elicited by target objects in constant-colour blocks, but should be strongly delayed or perhaps even entirely absent in variable-colour blocks. Furthermore, the costs of increasing colour load from one to two (Experiment 1) or from two to three (Experiment 2) should affect target N2pc amplitudes and latencies more strongly in variable-colour relative to constant-colour blocks.

Experiment 1

Method

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

Stimuli and procedure. Stimuli were presented on a 22-inch Samsung wide SincMaster 2233 LCD monitor with a 100 Hz refresh rate and at a resolution of 1280x1024 pixels. Participants were seated in a dimly illuminated test chamber, approximately 100 cm away from of the monitor. The Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.) running under Windows XP on a LG Pentium PC was used for stimulus presentation, timing and response recording. Two vertically aligned purpose-built response keys were employed to measure manual responses.

All stimuli were presented against a black background. A grey fixation point ($0.2^\circ \times 0.2^\circ$) was continuously present throughout each experimental block. Each trial started with the presentation of a cue display for 150 ms, which was followed by an 850 ms blank period, and a search array that was displayed for 150 ms (see Figure 1). The intertrial interval between the offset of a search array and the onset of the cue display on the next trial was temporally jittered between 1600 and 1800 ms. Cue displays contained two sets of two vertically aligned coloured squares, presented bilaterally to the left and right of fixation at a horizontal distance of 0.8° (measured relative to the centre of each square). The size of each individual square was 0.6° . In each hemifield, one square was presented at a vertical distance of 0.4° above and the other below the horizontal meridian. In half of all blocks, the squares on the right side of the cue display determined the target colour(s) for the upcoming search display. In the other half, the squares on the left side were task-relevant. The side of the relevant colour cue was alternated between blocks. Participants were informed about this task-relevant side by a written instruction on the computer screen that was presented at the start of each experimental block. Search displays contained four differently coloured digits and letters. The size of each of these items was $0.6^\circ \times 0.5^\circ$. Each of them was presented in a different quadrant of the visual field at a distance of 1° from the vertical and horizontal meridian (with respect to the centre of the stimulus). Digits (2, 4, 5, 6, 7, and 9) and capital letters (S, A, G, R, L, and P) were chosen randomly, without replacement, for each stimulus location in each search display. Possible stimulus colours in both cue and search arrays were red (CIE colour coordinates .627/.336), green (.263/568), blue (189/.193), yellow (.422/468), and magenta (.289/.168). All colours were equiluminant (~ 10.2 cd/m²).

Participants' task was to find the search item in the colour specified by the preceding cue display and to indicate its identity (digit or letter) with a left-hand or right-hand response. Key-to-category (top or bottom key for digit or letter) and hand-to-key assignments (left or right hand on top or bottom key) were counterbalanced across participants, but remained constant for each participant throughout the experiment. There were four different task conditions, for each of the four different combinations of colour load (One Colour task versus Two Colour task) and colour variability (constant-colour versus variable-colour conditions). These four conditions are illustrated in Figure 1. In the One Colour task, both cue display items on one side had one particular target colour (e.g., red). The two squares on the opposite side of the cue display had a different randomly assigned colour. For the Two Colour task, the five possible colours were combined into five sets of two target colours that were not adjacent in colour space and

therefore not linearly separable from the remaining nontarget colours (red or green, red or blue, green or magenta, blue or yellow, and yellow or magenta). The two cue display squares on the relevant side showed these two target colours, and the two squares on the opposite side showed two other randomly selected colours. The two colours on either side of the cue display were assigned randomly to the top and bottom square. Search arrays always contained four items in four different colours (one cued target colour, the colour/colours that appeared on the irrelevant side of the cue display, and one or two colours that did not appear in the cue display). Participants performed these One Colour and Two Colour tasks in two blocked variants. In the constant-colour condition, the target colours were fixed across all trials so that the cues always specified the same upcoming target colour(s) for each search array (e.g., red or green on trial 1, red or green on trial 2, red or green on trial 3, etc.). The fixed target colours were counterbalanced across participants. Each of the five possible colours (red, green, blue, yellow, or magenta) for the One Colour task, and each of the five two-colour sets for the Two Colour task was assigned to three of the 15 participants tested, with the restriction that there was no overlap between the target colours selected for the One and Two Colour tasks. In the variable-colour condition, the target colours changed from trial to trial, so that the cues showed a different (set of) target colour(s) on each trial (e.g., red and green on trial 1, blue and yellow on trial 2, green and magenta on trial 3, etc.). One of the five possible target colours (One Colour task) or target colour sets (Two Colour task) was randomly chosen on each trial, and all colours were presented equally often as cues and targets within each block.

Each participant completed six successive blocks of 40 trials for each of the four task conditions, resulting in 24 blocks and 960 experimental trials in total. Each block contained ten trials for each of the four target locations (top left, top right, bottom left, and bottom right) in the constant One Colour task, two trials for each of the 20 combinations of target location and target colour (red, green, blue, yellow, and magenta) in the variable One Colour task, five trials for each of the eight combinations of target location and target colour (one of the two colours from a fixed two-colour set) in the constant Two Colour task, and one trial for each of the 40 combinations of target location, target colour (one of two possible target colours), and target colour set (five possible two-colour sets) in the variable Two Colour task. The sequence of task conditions was counterbalanced across participants. Eight participants started with the variable-colour condition (One Colour task preceded by Two Colour task for four participants, and vice versa for the other four). The other seven participants started Experiment 1 with the constant-colour condition (One Colour task preceded by Two Colour task for four participants, and vice

versa for the remaining three). For all participants, the order of the One Colour and Two Colour tasks was reversed between the two halves of the experiment. All participants received 20 practice trials of the variable One Colour task before the start of the experimental blocks. No other training was provided during the experiment.

EEG recording and data analysis. The continuous EEG was DC-recorded from 27 scalp sites at standard positions of the extended 10/20 system, sampled at a rate of 500 Hz, and digitally low-pass filtered at 40 Hz. No further filters were applied after EEG acquisition. All electrodes were referenced to the left earlobe during recording, and were re-referenced offline to the average of both earlobes. Trials with artifacts (eye movements exceeding ± 30 μV in the HEOG channels; blinks exceeding ± 60 μV at Fpz; muscular movements exceeding ± 80 μV in all other channels), with incorrect, anticipatory (faster than 200 ms), very slow (slower than 1500 ms), or missing responses were excluded from EEG analyses. For the remaining trials, EEG signals were segmented within two time intervals (from 100 ms before to 1000 ms after cue display onset, and from 100 ms before to 400 ms after search display onset), to compute CDA components to cue displays and N2pc components to search displays, respectively. Separate averages were computed for each of the four task conditions (constant and variable One Colour and Two Colour tasks), separately for trials where the item of interest (the task-relevant cue or the target) appeared in the left or right visual field. CDA amplitudes were quantified in the basis of mean amplitudes obtained in the 300-1000 ms time window after cue array onset at lateral posterior electrodes PO7 and PO8. N2pc amplitudes were quantified on the basis of mean amplitudes obtained in the 200-300 ms time window after search array onset at the same lateral posterior electrodes. N2pc onset latencies were determined with a jackknife-based procedure (Miller, Patterson, & Ulrich 1998; Ulrich & Miller, 2001) on the basis of difference waveforms obtained by subtracting ERPs at electrodes PO7/8 ipsilateral to the side of a target from contralateral ERPs. With this procedure, onset latencies are estimated on the basis of grand-averaged difference waves of 15 subsamples, obtained by successively excluding one participant from the original sample. N2pc onset latencies were computed separately for each task condition and were defined as the point in time when the difference waveform for each subsample exceeded an absolute threshold value of -1 μV . This absolute threshold was determined as half of the jackknifed peak amplitude of the smallest N2pc (the smallest N2pc in Experiment 1 was the constant Two Colour N2pc with -2.0 μV). *F*- and *t*-values of the statistical comparisons were corrected according to the formula described by Miller et al. (1998), and Ulrich and Miller (2001),

and indicated with the labels ' F_c ' and ' t_c ', respectively. All t -tests were two-tailed and Bonferroni-corrected where necessary. Effect sizes are reported in terms of Cohen's d (Cohen, 1988), with a confidence interval of 95%, for t -tests and partial eta squared (η_p^2) for F -tests and t -test on jackknifed group means (jackknifed means were fed into one-way ANOVAs to allow for error variance correction according to the formula described by Ulrich and Miller, 2001). For all t -tests on N2pc latency measures, effect sizes are reported as corrected partial eta squared (labelled $\eta_p^2_c$, see Grubert and Eimer, 2016, for identical procedures).

Results

Behavioural results. 0.1% of all trials were excluded due to anticipatory (RTs < 200 ms) or very slow (RTs > 1500 ms) responses. Table 1 shows RTs and error rates for all four task conditions. Mean correct RTs were submitted to a repeated-measures ANOVA with the factors colour load (One Colour, Two Colour) and colour variability (constant-colour, variable-colour). A main effect of colour load, $F(1,14) = 146.3$, $p < .001$, $\eta_p^2 = .91$, demonstrated that RTs were faster in the One Colour (613 ms) relative to the Two Colour task (745 ms). RTs were also faster in constant-colour (646 ms) relative to variable-colour trials (712 ms), as reflected in a main effect of colour variability, $F(1,14) = 25.0$, $p < .001$, $\eta_p^2 = .64$. There was also a significant interaction between these two factors, $F(1,14) = 15.0$, $p = .002$, $\eta_p^2 = .52$, as the RT delay in the Two Colour task was larger in variable-colour blocks than in constant-colour blocks (158 ms versus 105 ms). An ANOVA on error rates also revealed main effects of colour load, $F(1,14) = 29.1$, $p < .001$, $\eta_p^2 = .68$, and colour-variability, $F(1,14) = 29.2$, $p < .001$, $\eta_p^2 = .68$, and an interaction, $F(1,14) = 12.8$, $p = .003$, $\eta_p^2 = .48$. Errors were more frequent in the Two Colour task relative to the One Colour task (6.0% versus 2.9%), and in variable-colour relative to constant-colour blocks (6.5% versus 2.4%). The increase of error rates in the Two Colour task relative to the One Colour task was more pronounced in variable-colour than in constant-colour blocks (4.8% versus 1.3%).

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

colour cues during the interval between cue and search displays, separately for the One Colour and Two Colour tasks in constant-colour and variable-colour blocks. CDA components were larger in variable-colour blocks relative to constant-colour blocks, and larger in the Two Colour task than in the One Colour task. This was confirmed by a repeated-measures ANOVA on ERP mean amplitudes measured in the 300-1000 ms window after cue display onset with the factors colour load, colour variability and laterality (electrode contralateral, ipsilateral to the target). This analysis revealed a main effect of laterality, $F(1,14) = 33.2, p < .001, \eta_p^2 = .70$, that interacted both with colour load, $F(1,14) = 19.2, p = .001, \eta_p^2 = .58$, and with colour variability, $F(1,14) = 37.9, p < .001, \eta_p^2 = .73$. There was no three-way interaction between laterality, colour load, and colour variability, $F(1,14) = 2.2, p = .163, \eta_p^2 = .13$, indicating that the increase of CDA amplitudes in the Two Colour relative to the One Colour task was similar in variable-colour and constant-colour blocks. Follow-up *t*-tests revealed that reliable CDA components were triggered in variable-colour blocks both for the Two Colour task ($-1.5 \mu\text{V}; t(14) = 6.0, p < .001, d = .85$) and the One Colour task ($-0.7 \mu\text{V}; t(14) = 5.2, p < .001, d = .50$). In constant-colour blocks, no reliable CDA was present in the One Colour task ($-0.1 \mu\text{V}; t(14) < 1$). However, a significant CDA was measured in the Two Colour task ($-0.4 \mu\text{V}; t(14) = 3.2, p = .006, d = .26$).

N2pc components to search displays. To address our main research question, we examined the N2pc component as a measure of the speed and efficiency of attentional deployments to target items in the search array. After trial exclusion, 89.3% of all trials remained in the analysis (ranging between 84.7% and 91.9% for the four task conditions). Figure 3 (top and middle panels) shows grand-average ERPs elicited at electrode sites PO7 and PO8 contra- and ipsilateral to the colour-defined target item in the search array during the 400 ms after search display onset. These ERPs are shown separately for the One and Two Colour tasks in blocks with constant or variable target colours. The panels on the bottom show N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs in the One Colour and Two Colour tasks, for constant-colour and variable-colour blocks. Solid target N2pc components were triggered in all four task conditions, and these N2pcs were attenuated and delayed in the Two Colour task relative to the One Colour task. Importantly, these effects of colour load on N2pc components appear very similar in constant-colour and variable-colour blocks. A repeated-measures ANOVA on N2pc mean amplitudes measured in the 200-300 ms time interval after search array onset, with the factors colour load, colour variability, and laterality confirmed this observation. A main effect of laterality, $F(1,14) = 55.8, p < .001, \eta_p^2 = .80$, was accompanied by an

interaction of colour load and laterality, $F(1,14) = 17.2$, $p = .001$, $\eta_p^2 = .55$, reflecting the larger N2pc amplitudes in the One Colour relative to the Two Colour task ($-2.3 \mu\text{V}$ versus $-1.5 \mu\text{V}$). There was no significant interaction between colour variability and laterality, $F(1,14) = 2.3$, $p = .148$, $\eta_p^2 = .14$, indicating that N2pc amplitudes did not differ systematically between constant-colour and variable-colour blocks. Critically, there was also no three-way interaction between colour load, colour variability, and laterality, $F(1,14) < 1$, which suggests that N2pc amplitude differences between the One and Two Colour tasks were equivalent in constant-colour and variable-colour blocks. Follow-up t -test demonstrated that N2pc components of all four task conditions were reliably elicited, all $t(14) > 5.5$, all $p < .001$, all $d > .32$. The N2pc latency differences between the One Colour and Two Colour tasks shown in the difference waveforms of Figure 3 were assessed with jackknife-based analyses. A repeated-measures ANOVA on N2pc onset latencies with the factors colour load and colour variability, revealed a main effect of colour load, $F_c(1,14) = 33.4$, $p < .001$, $\eta_p^2_c = .70$, as N2pc components emerged significantly earlier in the One Colour relative to the Two Colour task (194 ms versus 225 ms). Most importantly, there was no interaction between colour load and colour variability, $F_c(1,14) < 1$, indicating that this N2pc onset delay in the Two Colour task was equivalent in constant-colour and variable-colour blocks. This was confirmed by two follow-up t -tests which showed that N2pc onset latency differences between the One and Two Colour tasks were reliable and identical in size in constant-colour (199 vs. 230 ms; +31 ms) and variable-colour blocks (189 vs. 220 ms; +31 ms), both $t_c(14) > 4.2$, both $p < .002$, both $\eta_p^2_c = .59$. There was an unexpected tendency for N2pc components to emerge earlier in variable-colour blocks, but the main effect of colour variability on N2pc onset latencies was not reliable, $F_c(1,14) = 4.2$, $p = .060$, $\eta_p^2_c = .23$.

Discussion of Experiment 1

The pattern of CDA components observed in Experiment 1 in response to cue displays was consistent with previous results by Carlisle et al. (2011). In variable-colour blocks, reliable CDA components were elicited, and these components were larger in the Two Colour task relative to the One Colour task, reflecting the increased working memory load when participants prepare to search for two different possible target colours. In constant-colour blocks, CDA components were much smaller, which suggests that target templates in working memory were less strongly activated when participants searched for the same target-defining features across many trials. As in Carlisle et al. (2011), there was no reliable CDA in constant One Colour blocks. However, a

small but significant CDA was observed in blocks where participants searched for two constant target colours (Figure 2). If search templates are always completely transferred to long-term memory when target features remain constant (e.g., Carlisle et al., 2011), CDA components should have been absent in constant-colour blocks even when two colours were task-relevant. The presence of a significant CDA in constant Two Colour blocks suggests that when memory load is increased, colour-specific working memory representations remain activated to some degree. However, and most importantly, the strong attenuation of CDA components in constant-colour relative to variable-colour blocks suggests that target templates were stored in a different format in these two types of blocks. One possibility is that they were primarily held in long-term memory when target colours remained constant, and in working memory when these colours were variable (see below for an alternative interpretation of the CDA differences between variable- and constant-colour blocks).

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

The observation that the effects of increasing colour load on the latency and amplitude of target N2pc components were essentially identical in constant-colour and variable-colour blocks is important, because it suggests that there are no systematic differences between search templates in working memory and in a longer-term memory store in their ability to guide attentional target selection. In sharp contrast to the hypothesis that templates in long-term memory facilitate efficient target selection during multiple-feature search whereas templates in working memory do not, the N2pc results of Experiment 1 suggest that there are no capacity

differences between these two types of templates. It should be noted that the behavioural costs of increasing colour load were larger with variable as compared to constant target mappings, in line with previous findings (e.g., Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In addition, there was also a general delay of RTs and an increase in error rates in variable-colour as compared to constant-colour blocks. As will be further considered in the General Discussion, these behavioural costs of variable target colour mappings are likely to be generated at stages beyond the initial allocation of attention to target objects, as reflected by the N2pc.

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

Experiment 2

Method

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

Stimuli and procedure. Procedures were the same as in Experiment 1, except as stated below. Four different task conditions were run, and two of them (the constant and variable Two Colour tasks) were identical to Experiment 1. In the other two task conditions, participants performed a constant or variable Three Colour task where the target item in the search display could have one out of three equally likely target colours (e.g., red, green, or blue). In this task, the bilateral cue arrays contained two sets of three differently coloured squares. The two vertically aligned squares on each side appeared in the same locations as in the Two Colour task, but they were now accompanied by an additional square that appeared at a horizontal distance of 1.9° from fixation (measured relative to the centre of this square; see Figure 1). As in the Two Colour task, one of these sets of coloured squares indicated the possible target colours for the upcoming search array, and the side of these task-relevant squares was alternated between blocks. As in Experiment 1, participants' task was to identify the category (digit, letter) of the search display item that matched one of the cued target colours. The set of five possible target-defining colours and the assignment of target colours in the Two Colour task were identical to Experiment 1. In the constant-colour Three Colour task, each participant searched for those three colours that did not serve as their target colours in the constant-colour Two Colour task. This procedure resulted in five possible constant three-colour target sets (red, blue, or yellow; red, green, or blue; red, green, or magenta; green, yellow, or magenta; and blue, yellow, or magenta). In the variable-colour Three Colour task, one of these three-colour target sets was selected randomly on each trial. Distractor colours in both cue and search arrays were chosen randomly from the set of currently task-irrelevant colours. This set contained an additional equiluminant grey (CIE colour coordinates .323/.353; $\sim 10.2 \text{ cd/m}^2$), which was necessary to avoid distractor colour repetition in the Three Colour task.

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

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

Results

Behavioural results. 1.8% of all trials were excluded due to anticipatory (RTs < 200 ms) or very slow (RTs > 1500 ms) responses. Table 1 shows RTs and error rates for all four task conditions. A repeated-measures ANOVA with the factors colour load (Two Colour, Three Colour) and colour variability (constant-colour, variable-colour) on mean correct RTs revealed a main effect of colour load, $F(1,14) = 72.2, p < .001, \eta_p^2 = .84$, with faster RTs in the Two Colour task relative to the Three Colour task (743 ms versus 848 ms), as well as a main effect of colour variability, $F(1,14) = 23.5, p < .001, \eta_p^2 = .63$, reflecting faster responses in constant-colour relative to variable-colour blocks (755 ms versus 836 ms). There was no interaction between these two factors, $F(1,14) < 1$, indicating that the effects of increased colour load on RTs did not differ systematically between constant-colour blocks (112 ms) and variable-colour blocks (99 ms). For error rates, the same overall pattern was observed. There were main effects of colour load, $F(1,14) = 49.7, p < .001, \eta_p^2 = .78$, and colour variability, $F(1,14) = 37.9, p < .001, \eta_p^2 = .73$, with more incorrect responses in the Three Colour as compared to the Two Colour task (12.4% versus 4.4%), and in variable-colour as compared to constant-colour blocks (11.6% versus 5.2%). An interaction between these two factors, $F(1,14) = 24.4, p < .001, \eta_p^2 = .64$, was due to the fact that the increase in error rates in the Three Colour relative to the Two Colour task was more pronounced on variable-colour blocks (11.3%) than in constant-colour blocks (4.6%).

CDA components to cue displays. 75.4% of all trials remained in the analysis after the exclusion of trials with errors or artefacts and slow, fast or missing responses (ranging between 71.3% and 79.9% for the four task conditions). Figure 4 shows grand-average ERPs elicited at PO7/8 contra- and ipsilateral to the task-relevant colour cues during the interval between cue and search displays, separately for the Two and Three Colour tasks in constant-colour and variable-colour blocks. As in Experiment 1, CDA components were generally larger in variable-colour blocks than in constant-colour blocks, although a CDA also appears to be present in blocks with two or three constant target colours. Furthermore, increasing the colour load from two to

three resulted in the expected increase of CDA amplitudes. A repeated-measures ANOVA on ERP mean amplitudes measured in the 300-1000 ms window after cue display onset with the factors colour load, colour variability and laterality revealed a main effect of laterality, $F(1,14) = 47.1$, $p < .001$, $\eta_p^2 = .77$, that interacted with colour variability, $F(1,14) = 40.5$, $p < .001$, $\eta_p^2 = .74$, thus confirming the observation that CDA components were larger in variable-colour blocks. There was also an interaction between colour load and laterality, $F(1,14) = 11.3$, $p = .005$, $\eta_p^2 = .45$, reflecting the increase of CDA amplitudes in Three Colour as compared to Two Colour blocks. As in Experiment 1, there was no three-way interaction between laterality, colour load, and colour variability, $F(1,14) = 2.3$, $p = .152$, $\eta_p^2 = .14$, indicating that the increase of CDA amplitudes with increased colour load did not differ between variable-colour and constant-colour blocks. Follow-up t -tests confirmed the presence of reliable CDA components in variable-colour blocks ($-1.4 \mu\text{V}$ and $-2.0 \mu\text{V}$ for the Two and Three Colour tasks), as well as in constant-colour blocks ($-0.3 \mu\text{V}$ and $-0.6 \mu\text{V}$ for the Two and Three Colour tasks), all $t(14) > 3.0$, all $p < .009$, all $d > .18$.

N2pc components to search displays. After trial exclusion, 80.0% of all trials remained in the analysis (ranging between 70.6% and 86.1% for the four task conditions). Figure 5 (top and middle panels) shows grand-average ERPs elicited at PO7/8 contra- and ipsilateral to the colour-defined target item during the 400 ms after search display onset, separately for the Two and Three Colour tasks, and blocks with constant or variable target colours. The corresponding N2pc difference waveforms in the Two Colour and Three Colour tasks are shown in the bottom panels, separately for constant-colour and variable-colour blocks. N2pc components were again solid in all four task conditions, but were attenuated and delayed in the Three Colour task relative to the Two Colour task. Importantly, and analogous to Experiment 1, these effects of colour load on target N2pc component were similar in constant-colour and variable-colour blocks. A repeated-measures ANOVA on N2pc mean amplitudes measured in the 200-300 ms time interval after search array onset with the factors colour load, colour variability, and laterality obtained a main effect of laterality, $F(1,14) = 50.2$, $p < .001$, $\eta_p^2 = .78$, as well as an interaction between colour load and laterality, $F(1,14) = 11.0$, $p = .005$, $\eta_p^2 = .44$. This was due to the fact that N2pc components were larger in the Two Colour relative to Three Colour task ($-1.4 \mu\text{V}$ versus $-0.9 \mu\text{V}$). There was no significant interaction between colour variability and laterality, $F(1,14) = 1.7$, $p = .217$, $\eta_p^2 = .11$, demonstrating that as in Experiment 1, there were no systematic N2pc amplitude differences between constant-colour and variable-colour blocks. Most importantly, the absence of a three-way interaction between colour load, colour variability, and laterality, $F(1,14) = 1.2$, $p =$

.301, $\eta_p^2 = .08$, indicated that the reduction of N2pc amplitudes with the increase in colour load was the same in constant- and variable-colour blocks. Follow-up *t*-test confirmed that reliable N2pc components were present in all four task conditions, all $t(14) > 3.3$, all $p < .005$, all $d > .26$. The N2pc onset delay in the Three Colour task relative to the Two Colour task that is evident in the difference waves of Figure 5 was assessed with jackknife-based analyses. There was a main effect of colour load, $F_c(1,14) = 12.8$, $p = .003$, $\eta_p^2 = .48$, confirming that the N2pc emerged later in the Three Colour task than in the Two Colour task (226 ms versus 207 ms). There was no main effect of colour variability, and no interaction between colour load and colour variability, both $F_c(1,14) < 1$, indicating that N2pc onset latencies did not differ between constant-colour and variable-colour blocks. Follow-up *t*-tests showed that the N2pc onset delay in the Three Colour relative to the Two Colour task was reliably present both in constant-colour blocks (226 ms versus 209 ms; +17 ms) and in variable-colour blocks (226 ms versus 204 ms; +22 ms), both $t_c(14) > 2.3$, both $p < .033$, both $\eta_p^2 > .28$.

Discussion of Experiment 2

The results obtained in Experiment 2 were very similar to Experiment 1. Again, CDA amplitudes measured in response to cue displays were much larger in variable-colour relative to constant-colour blocks, indicating that search templates in working memory were more strongly activated when target colours changed between trials, and that these templates were at least partially transferred to long-term memory in blocks with constant target colours. In variable-colour blocks, CDA components were larger for the Three Colour task as compared to the Two Colour task, reflecting the difference between the retention of three versus two possible target colours in working memory. As in Experiment 1, a small but reliable CDA was present in constant-colour blocks for the Two Colour task, and this component was larger in the Three Colour task (Figure 4). This again suggests that target representations are not completely handed off to long-term memory when target features remain constant, but that search templates in working memory are still activated to some degree under these conditions, in particular when memory load is high.

Most importantly, the pattern of N2pc components to target objects in constant-colour and variable-colour blocks confirmed the observations of Experiment 1. Again, there were no systematic N2pc differences between these two types of blocks (see Figure 5, bottom panel). In both constant-colour and variable colour-blocks, N2pc components were attenuated and

emerged about 20 ms later when participants searched for three as compared to two possible target colours, demonstrating that the increase of colour memory load slightly impaired the allocation of attention to target objects. The fact that this delay did not differ between constant-colour and variable-colour blocks in Experiment 2 again suggests that there are no systematic differences between the capacity of target templates in long-term and working memory. As in Experiment 1, these electrophysiological results contrasted with the effects of colour variability on behavioural performance, with slower RTs and increased error rates in variable-colour blocks, and a much steeper increase in error rates for the Three Colour versus Two Colour task in these blocks relative to constant-colour blocks.

General Discussion

The goal of the present study was to find out whether the deployment of attention to target objects during multiple-colour search is more efficient when target-defining colours remain constant than when they vary across trials. We compared the guidance of attentional target selection by multiple-colour templates in blocks where target colours were constant and could thus be represented in long-term memory and blocks where they were variable and therefore had to be held in working memory. Target colours (one versus two in Experiment 1, two versus three in Experiment 2) were specified by cue displays that preceded search displays on each trial, and these colours either remained the same in four successive blocks, or varied across individual trials.

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

high-reward trials, suggesting that driving attention from both long-term and working memory may be a strategic choice to improve performance.

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

If repeatedly searching for the same set of target features results in an automatization of the search process (e.g., Schneider & Shiffrin, 1977) that is linked to a transfer of search templates from capacity-limited working memory to a long-term memory store with unlimited capacity (e.g., Carlisle et al., 2011), template-guided attentional target selection during multiple-colour search should have been much more efficient in constant-colour as compared to variable-colour blocks. The pattern of target N2pc results obtained in the present study did not support this hypothesis. N2pc components to colour-defined search targets were virtually identical in constant-colour and variable-colour blocks, and this was not only the case for the One Colour task but also for the Two Colour and Three Colour tasks. Increasing the number of possible target

colours from one to two (Experiment 1) or from two to three (Experiment 2) resulted in significantly delayed and attenuated N2pc components, demonstrating systematic costs of colour load on the deployment of attention to target objects (see below for further discussion). Critically, these costs were virtually identical in constant-colour and variable-colour blocks, and this was the case in both experiments. If target templates are held in working memory in variable-colour blocks and in long-term memory in constant-colour blocks, the absence of any load-dependent N2pc differences between these blocks indicates that these two types of templates are equivalent in their capacity and thus in their ability to guide attention towards the location of target objects during single-colour and multiple-colour search.¹ Alternatively, this pattern of N2pc results might suggest that target templates were maintained in working memory in both constant and variable target colours, but in a different spatial format (see above).

In contrast to the absence of any differential effects of colour variability on target N2pc components, behavioural performance was strongly affected when target colours varied across trials. There was a substantial RT delay in variable-colour relative to constant-colour blocks (65 ms in Experiment 1 and 81 ms in Experiment 2) that was accompanied by a corresponding increase in error rates (4.0% and 6.3%, respectively), in line with previous observations from visual search studies that compared constant and variable target mappings (e.g., Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In addition, the behavioural costs produced by

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

increasing colour load were more pronounced in variable-colour blocks. This was the case both for RTs and error rates in Experiment 1, and only for error rates in Experiment 2. Given the absence of any N2pc differences between constant-colour and variable-colour blocks, these performance costs must be generated at processing stages beyond the rapid allocation of spatial attention to template-matching objects that is reflected by the N2pc. Shiffrin and Schneider (1977) distinguish three successive processes that jointly contribute to the automatization of search processes with constant target mappings – the rapid allocation of attention to target-matching features in a search display, the subsequent identification of a target object that is based on a comparison with a stored representation of target-defining features, and the selection of the response assigned to this particular target. The N2pc results obtained in the present study strongly suggest that the first of these three processes (i.e., the attentional selection of target features) was not selectively impaired with variable as compared to constant target mappings. Because the target-defining dimension (colour) differed from the response-relevant dimension (alphanumeric category) in the present study, it is unlikely that response-related processes were responsible for the behavioural costs observed in variable-colour blocks. This leaves the target identification process specified by Shiffrin and Schneider (1977) as the main source of these costs. Target selection and target identification are dissociable processes during visual search (e.g., Wolfe, 2007; see also Eimer, 2014, 2015, for further discussion), with identification depending on a comparison between the visual features of a selected object and a currently active target template. In line with Shiffrin and Schneider (1977), this comparison process may operate less rapidly and accurately when possible target features change across trials, in particular when multiple features are simultaneously task-relevant, and this could account for the pattern of behavioural costs in variable-colour blocks.²

² An electrophysiological marker for target identification processes that is elicited after the allocation of spatial attention to candidate target objects is the sustained contralateral posterior negativity (SPCN component; Mazza, Turatto, Umiltà, & Eimer, 2007; Jolicoeur, Brisson, & Robitaille, 2008). The SPCN typically emerges around 350 ms after target display onset, and is assumed to be linked to the activation of target representations in visual working memory during the identification and categorization of target objects. In the present study, SPCN components followed the N2pc to target objects at post-stimulus latencies of around 350-700 ms (not shown in Figures). For Experiment 1, analyses of SPCN mean amplitudes showed that this component was larger during variable-colour relative to constant-colour blocks, $F(1,14) = 12.4$, $p = .003$, $\eta_p^2 = .47$, in line with a more sustained activation of visual working memory during target identification in variable-colour blocks. However, because no such SPCN amplitude differences between variable-colour and constant-colour blocks were found in Experiment 2, $F(1,14) < 1$, this conclusion requires additional confirmation in future studies.

In contrast to colour variability, colour load had a reliable effect on target N2pc components in the present experiments. N2pc components were attenuated and delayed during search for two versus one possible target colours in Experiment 1, and an additional N2pc attenuation and delay was observed for the Three Colour task in Experiment 2. These results demonstrate impairments in the deployment of spatial attention to target objects during multiple-colour search independently of whether target templates were held in working or long-term memory. It is notable that the onset delay of N2pc components in the Two Colour versus One Colour tasks of Experiment 1 (31 ms) and in the Three Colour versus Two Colour tasks of Experiment 2 (19 ms) was much smaller than the corresponding difference of target RTs between these tasks (132 ms and 106 ms, respectively), which suggests that a delayed allocation of attention to target objects was only partially responsible for the RT costs during multiple-colour search. While the pattern of delayed N2pc onsets was similar to the N2pc delays observed in our previous experiments (Grubert & Eimer, 2013, 2015), target N2pc components were also attenuated for two-colour versus one-colour search, and for three-colour versus two-colour search in the present study (see Figures 3 and 5, bottom panels). This attenuation suggests that attention may not have been deployed at all to colour-defined search targets within the N2pc time window on a substantial number of trials when two or three colours were task-relevant. To investigate this possibility, N2pc components measured in Experiment 1 were computed separately for trials with fast and slow target responses, based on RT median splits performed for each individual participant, and for each of the four combinations of colour load and colour variability. Figure 6 shows N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs on trials with fast and slow RTs, separately for the One and Two Colour tasks in variable-colour and constant-colour blocks. In the One Colour task, clear target N2pc components were present both for trials with fast and slow responses, and there were no significant N2pc amplitude differences between these trials, both $t(14) < 1.6$, both $p > .13$. This shows that attention was rapidly deployed to the search target on the vast majority of all trials during single-colour search. In the Two Colour task, large N2ps were present on fast response trials, but these components were reliably attenuated on trials with slow RTs, both in constant-colour and variable-colour blocks, both $t(14) > 5.3$, both $t < .001$, both $d > 1$. This demonstrates that on a substantial number of Two Colour trials, the allocation of attention to the colour-defined target object was considerably delayed, resulting in slow target discrimination responses on these trials.

What do these observations imply for the issue of attentional templates for multiple target features? If such templates are activated simultaneously during search for multiple

possible target colours, they should be able to guide attention efficiently to colour-defined target objects. The marked attenuation of target N2pc during multiple-colour search observed in the present study, in particular for trials with slow responses, suggests instead that representations of target-defining colours were either not fully activated during the preparation for an upcoming search display, or were not always effective in controlling the subsequent deployment of attention to colour-matching objects. The observation that CDA components elicited in response to cue displays in variable-colour blocks were larger when these cues specified two target colours rather than a single colour, and larger still in the Three Colour task indicates that all target-defining colours were represented simultaneously in working memory. However, the attenuation of target N2pc components during multiple-colour search demonstrates that the guidance of attention by these representations was less effective than during search for a single target colour. To provide further support for this hypothesis, CDA components measured in the Variable Two Colour task of Experiment 1 were computed separately for trials with fast versus slow responses. There were no systematic CDA amplitude differences between these two types of trials, $F(1,14) < 1$, indicating that the reduction of target N2pc components on slow response trials was not linked to insufficient colour-specific preparation but instead to impaired attentional guidance by target colour templates during multiple-colour search. It is possible that while all target colours were stored in memory, only one of these was actively prioritized and thus able to control the subsequent deployment of attention, while the others were less active “accessory items” (e.g., Olivers et al., 2011) and had no impact on attentional target selection processes. This hypothesis that only a single colour-specific attentional template can be activated on any given trial predicts that relative to single-colour search, N2pc components during the Two Colour task of Experiment 1 should be reduced in size by 50%, because a target-colour item would match the currently active search template on only half of all trials. In fact, the target N2pc amplitudes decreased only by about 35% between the One Colour and Two Colour tasks (averaged across variable-colour and constant-colour blocks), suggesting that on a subset of two-colour search trials, templates for both target colours were active. Thus, the current findings do not provide clear-cut electrophysiological support for the single-template hypothesis. They do however demonstrate that the allocation of attention to target objects during multiple-colour as compared to single-colour search is impaired, which challenges the assumption that multiple feature-specific attentional task sets can be activated simultaneously without mutual interference (see Grubert & Eimer, 2015, for a similar suggestion).

The impaired attentional target selection during multiple-colour search observed in the present study even when target colours remained constant may appear inconsistent with previous behavioural and electrophysiological studies which have found evidence for simultaneous attentional task sets for multiple colours (e.g., Moore & Weissman, 2010; Irons et al., 2012; Grubert & Eimer, 2013, 2015, in press). It is, however, notable that in all of these experiments, the demands on colour-based attentional selectivity were generally very low. The cue displays employed by Irons et al. (2012) and Grubert & Eimer (in press) always contained one colour singleton item among uniform white or grey items. In the N2pc experiments by Grubert & Eimer (2013, 2015), individual stimulus displays only included two items on opposite sides. Moore & Weissman (2010) presented three objects in each stimulus display, but target objects always appeared at fixation, obviating the need for any colour-based spatial selection. In contrast, there were always four objects in four colours in the search displays that were employed in the current study. Even though this stimulus set size is relatively small when compared to standard behavioural visual search experiments, the fact that four different colours were present in each search display required that participants adopted a highly selective task set for the colour(s) that were currently task-relevant in order to find the target object. It is possible that attentional sets for multiple colours are relatively effective in guiding attention in tasks where the colour-based spatial selection of individual objects is easy, and that the limitations of such task sets only become apparent when these task demands are increased. This needs to be investigated more systematically in future research.

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

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	Constant-colour blocks		Variable-colour blocks	
	RTs (ms)	Error rates (%)	RTs (ms)	Error rates (%)
Experiment 1				
One Colour task	594 [83]	1.8 [1.3]	632 [93]	4.0 [3.7]
Two Colour task	699 [104]	3.1 [2.6]	791 [133]	8.9 [4.6]
Experiment 2				
Two Colour task	699 [86]	2.9 [2.7]	787 [96]	5.9 [3.5]
Three Colour task	811 [109]	7.6 [5.5]	886 [82]	17.2 [7.6]

Table 1. RTs (in milliseconds) and error rates (percentage correct) in the One Colour, Two Colour and Three Colour tasks of Experiment 1 and 2, separately for constant-colour and variable-colour blocks. Square brackets specify standard deviations from the mean.

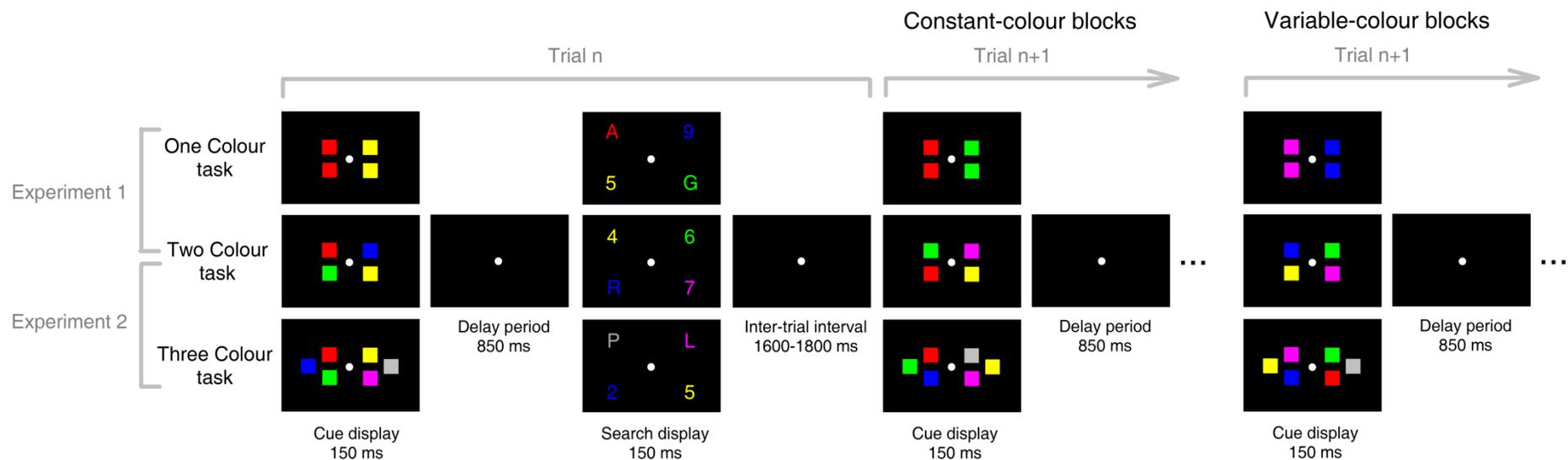


Figure 1. Schematic illustration of a constant-colour and variable-colour trial sequence in the One Colour, Two Colour, and Three Colour tasks of Experiment 1 and 2. Each trial started with the presentation of a bilateral cue display, specifying one, two, or three possible target colour(s) for the subsequent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

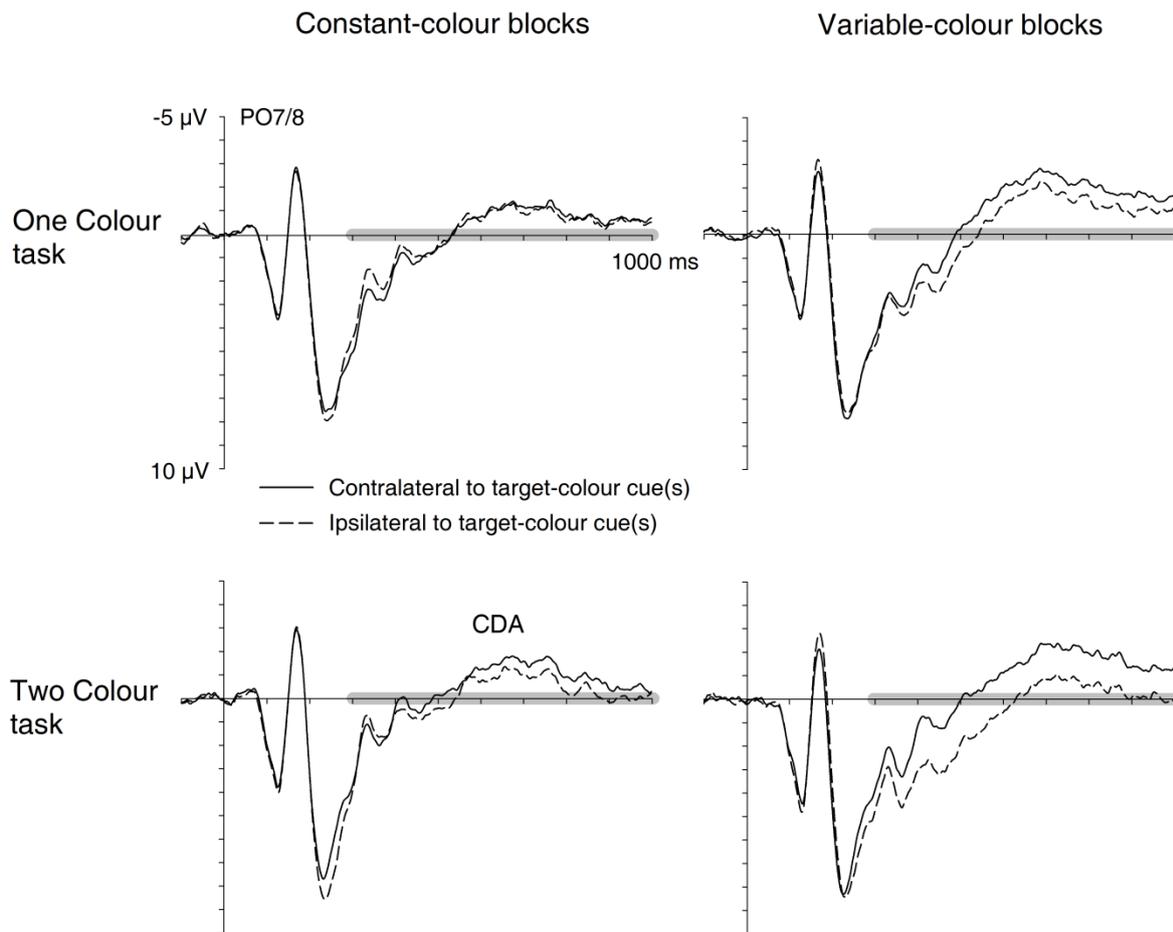


Figure 2. Cue-locked grand-average ERPs measured in constant-colour blocks (left panel) and variable-colour blocks (right panel) of the One Colour (top panel) and Two Colour tasks (bottom panel) of Experiment 1. ERPs are shown for the 1000 ms interval after cue array onset, at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the task-relevant target-colour cues. CDA components were measured in the 300-1000 ms post-stimulus interval (grey bar on x-axis).

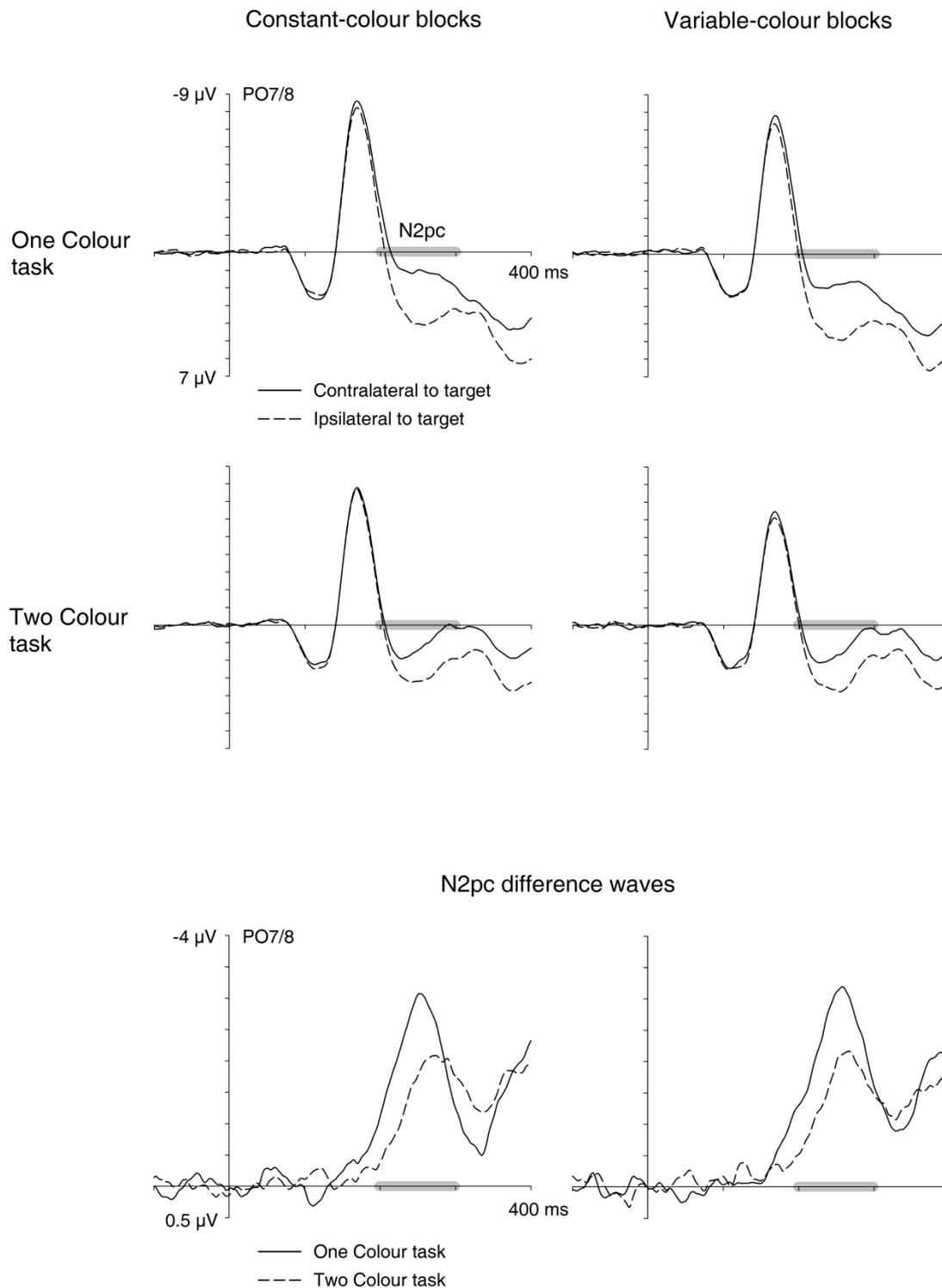


Figure 3. Target-locked grand-average ERPs measured in constant-colour blocks (left panel) and variable-colour blocks (right panel) of the One Colour (top panel) and Two Colour tasks (middle panel) of Experiment 1. ERPs are shown in the 400 ms interval after search array onset, at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the colour-defined target item. The bottom panel shows N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. N2pc components were measured in the 200-300 ms post-stimulus interval (grey bar on x-axis).

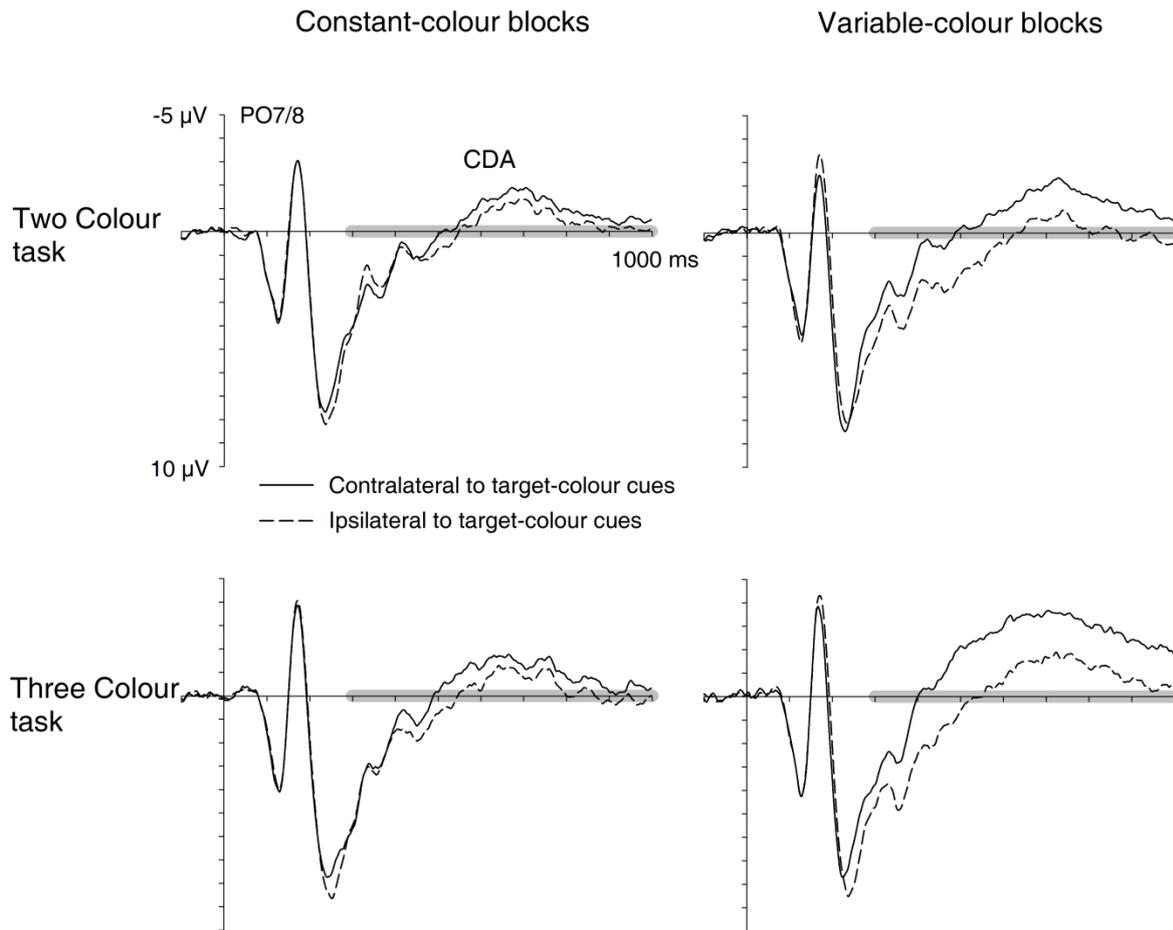


Figure 4. Cue-locked grand-average ERPs measured in constant-colour blocks (left panel) and variable-colour blocks (right panel) of the Two Colour (top panel) and Three Colour tasks (bottom panel) of Experiment 2. ERPs are shown for the 1000 ms interval after cue array onset, at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the task-relevant target-colour cues. CDA components were measured in the 300-1000 ms post-stimulus interval (grey bar on x-axis).

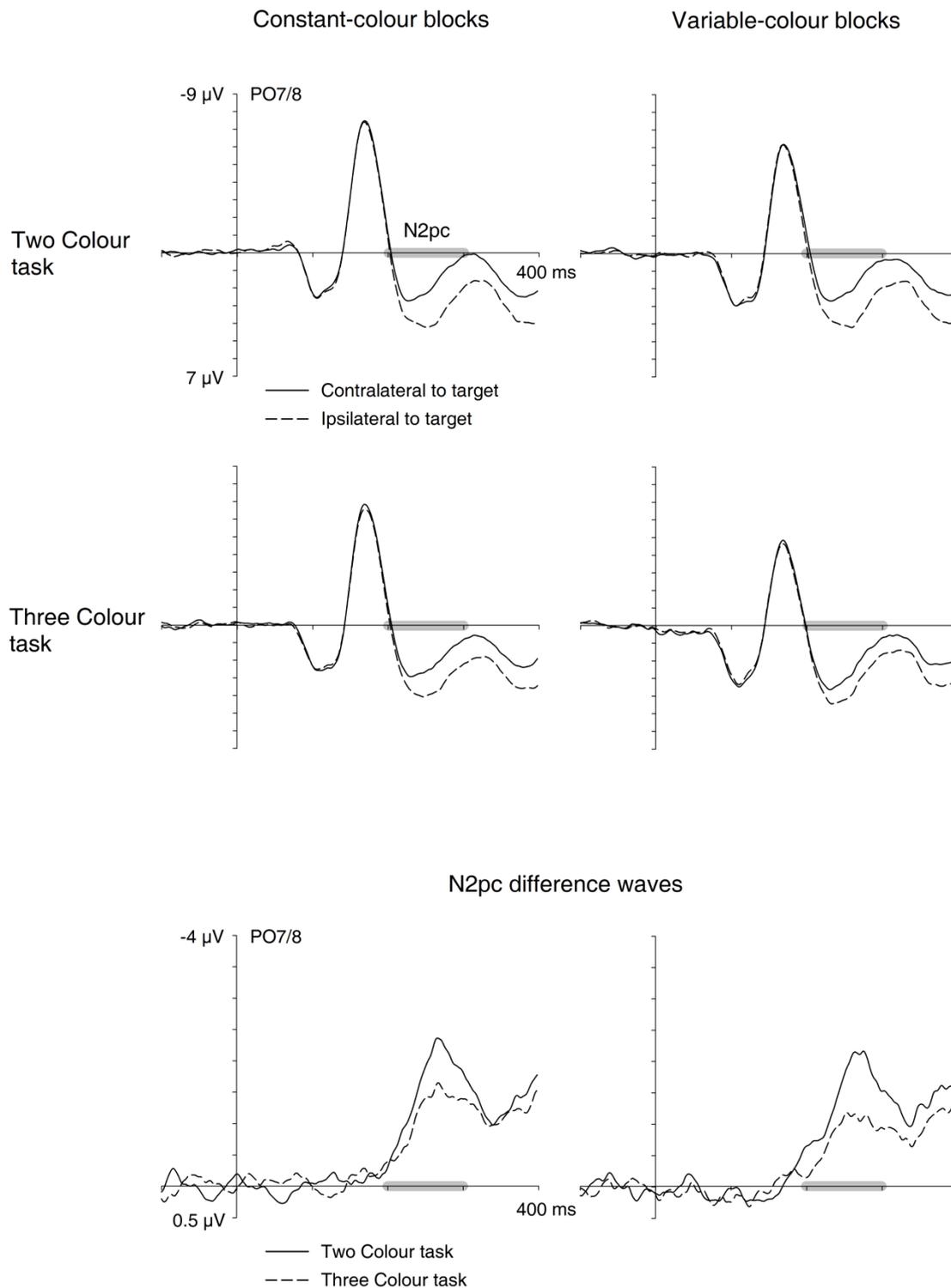


Figure 5. Target-locked grand-average ERPs measured in constant-colour blocks (left panel) and variable-colour blocks (right panel) of the Two Colour (top panel) and Three Colour tasks (middle panel) of Experiment 2. ERPs are shown in the 400 ms interval after search array onset, at posterior electrodes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

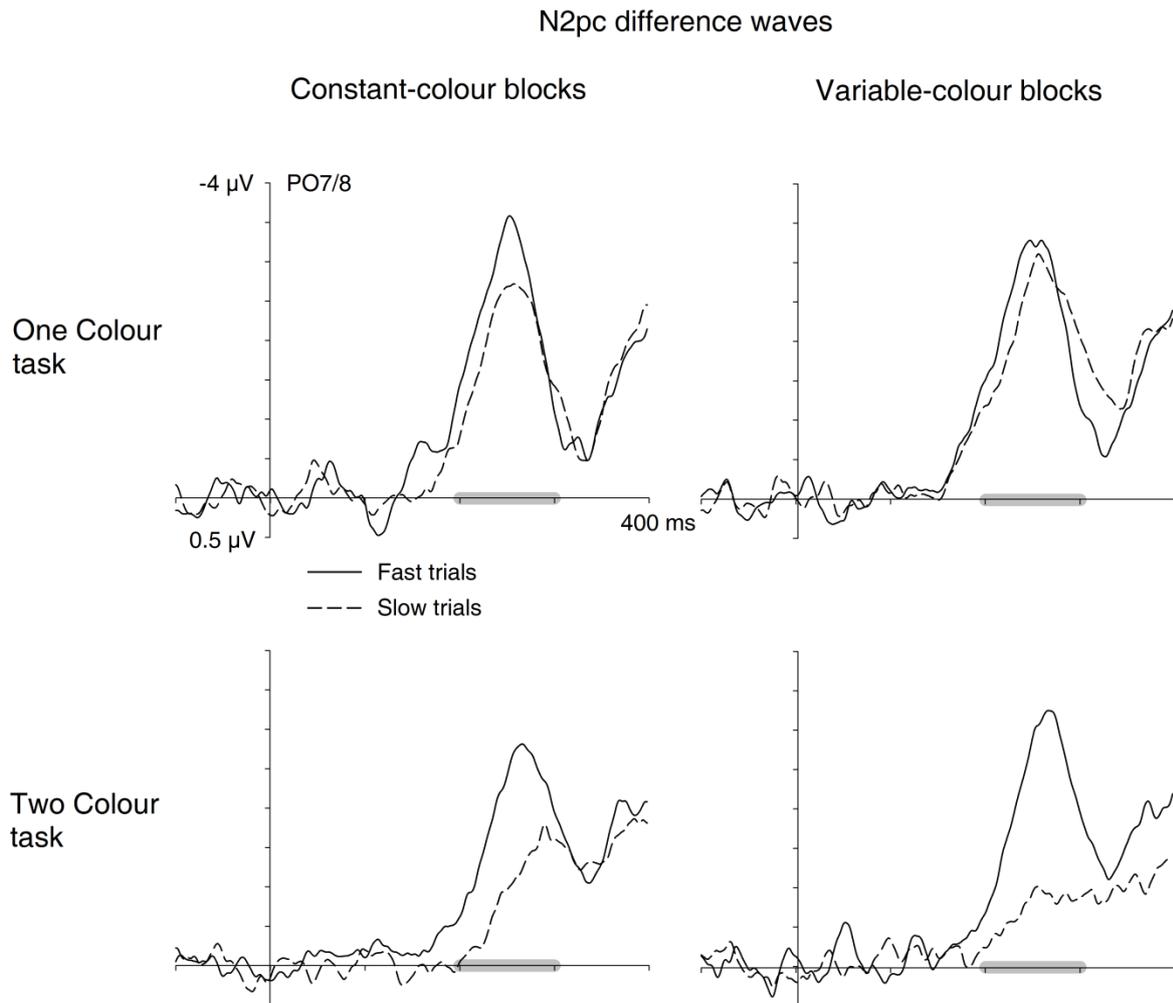


Figure 6. N2pc difference waveforms in variable-colour and constant-colour blocks of the One Colour and Two Colour tasks of Experiment 1, shown separately for trials with fast and slow RTs (based on RT median splits performed for each individual participant and task condition).