The guidance of spatial attention during visual search
for colour combinations and colour configurations

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ABSTRACT

Representations of target-defining features (attentional templates) guide the selection of target objects in visual search. We used behavioural and electrophysiological measures to investigate how such search templates control the allocation of attention in search tasks where targets are defined by the combination of two colours or by a specific spatial configuration of these colours. Target displays were preceded by spatially uninformative cue displays that contained items in one or both target-defining colours. Experiments 1 and 2 demonstrated that, during search for colour combinations, attention is initially allocated independently and in parallel to all objects with target-matching colours, but is then rapidly withdrawn from objects that only have one of the two target colours. In Experiment 3, targets were defined by a particular spatial configuration of two colours, and could be accompanied by nontarget objects with a different configuration of the same colours. Attentional guidance processes were unable to distinguish between these two types of objects. Both attracted attention equally when they appeared in a cue display, and both received parallel focal-attentional processing and were encoded into working memory when they were presented in the same target display. Results demonstrate that attention can be guided simultaneously by multiple features from the same dimension, but that these guidance processes have no access to the spatial-configural properties of target objects. They suggest that attentional templates do not represent target objects in an integrated pictorial fashion, but contain separate representations of target-defining features.

Keywords: selective attention; top-down control; spatial cueing; event-related brain potentials; feature-based attention

INTRODUCTION

During visual search, the features of target objects are represented in visual working memory. Such representations have been conceptualised as attentional templates (e.g., Desimone & Duncan, 1995) or top-down task sets (e.g., Folk, Remington, & Johnston, 1992). Search templates are activated prior to the start of a particular search episode, and bias attention towards target-matching visual features (e.g., Olivers, Peters, Houtkamp, & Roelfsema, 2011; Eimer, 2014). In computational models of visual search (e.g., Wolfe, 1994, 2007), attentional templates are implemented as top-down weights. These weights regulate the contribution of signals from different feature channels on the activation profile of a central salience map, which in turn guides the allocation of attention towards particular objects during visual search.

To understand the role of attentional templates in the control of visual search, it is important to determine how information about task-relevant objects is represented in these templates, and how this information then affects the deployment of attention to objects with template-matching features. Numerous studies have investigated how efficiently search templates for one particular target feature (e.g., the colour red) or feature dimension (e.g., colour in general) can guide attention during visual search (see Wolfe & Horowitz, 2004, for a review). However, target objects in real-world search are often defined not just by one specific feature or dimension, but by a particular combination of features from the same or from different dimensions. In such tasks, the allocation of attention has to be controlled by more complex search templates that represent multiple target attributes. In the Guided Search model (Wolfe, 1994, 2007), templates for targets that are defined by a conjunction of features from different dimensions (e.g., red squares) guide attention by biasing template-matching feature channels in different dimensions independently and in parallel. As a result, a target object with all task-relevant features elicits more activation on the salience map than nontarget objects with a single target feature (e.g., green squares or red circles), and is therefore more likely to attract focal attention during visual search. Importantly, Guided Search assumes that search templates represent only a single target attribute within a particular dimension such as colour (Wolfe, 2007). In line with this assumption, template-guided search is inefficient when target objects are defined by a combination of features from the same dimension (e.g., a red and green object; see Wolfe et al., 1990).

Spatial cueing procedures are a useful way to assess the effects of search templates for single target features or feature combinations on attentional guidance processes. In cueing

tasks, visual search displays are preceded by spatially uninformative and task-irrelevant cue displays. In spite of the instruction to ignore them, feature singleton cues with a unique target-matching feature will capture attention, as reflected by faster reaction times (RTs) to subsequent search targets that appear at the same location as the cue relative to target objects at other uncued locations (e.g., Folk et al., 1992; Folk & Remington, 1998). The fact that no such spatial cueing effects are elicited by singleton cues that do not match a currently active attentional template demonstrates that this type of rapid involuntary attentional capture is elicited in a task-set contingent fashion only by objects with target-matching features. Further electrophysiological evidence for this comes from event-related brain potential (ERP) experiments that measured the N2pc component as a marker of attentional selectivity. The N2pc is an enhanced negativity that emerges approximately 200 ms after the onset of a search display over posterior electrodes contralateral to the visual field of objects with features that match the current search template, and is assumed to reflect the allocation of spatial attention to these objects (e.g., Eimer, 1996; Luck & Hillyard, 1994). In line with task-set contingent attentional capture (Folk et al., 1992), template-matching colour singleton cues (e.g., red singleton cues during search for red targets) trigger N2pc components, while nonmatching cues do not (e.g., red singleton cues during search for blue targets or small targets; e.g., Eimer & Kiss, 2008; Leblanc, Prime, & Jolicoeur, 2008; Lien, Ruthruff, Goodin, & Remington, 2008). The presence of an N2pc to template-matching but task-irrelevant objects shows that these objects capture attention at a relatively early stage of visual-perceptual processing. Analogous behavioural and electrophysiological attentional capture effects have also been found when template-matching colour cues appear among other coloured items in heterogeneous cue displays, demonstrating that objects do not need to be perceptually salient singletons in order to attract attention in a task-set contingent fashion (Eimer, Kiss, Press, & Sauter, 2009; Lamy, Leber, & Egeth, 2004).

Most behavioural and electrophysiological spatial cueing experiments have used tasks where search targets were defined by one particular feature. However, this paradigm can also be employed to study the operation of more complex target templates. For example, Irons, Folk, and Remington (2012) have investigated whether search templates can be set simultaneously for multiple target colours. Participants searched for either of two coloured targets (e.g., red or green items) in search arrays where a target was presented together with a task-irrelevant colour distractor (e.g., a blue item). Search arrays were preceded by task-irrelevant displays that contained a colour singleton cue. Cues that matched one of the two target colours elicited spatial cueing effects indicative of attentional capture. Importantly, no

such effects were elicited by non-matching cues, suggesting that other colours were successfully excluded from the currently active search templates. This was the case even when matching and non-matching cues were not linearly separable in colour space. Irons et al. (2012) interpreted these findings as evidence that observers can adopt a simultaneous task set for two different colours (see also Christie, Livingstone, & McDonald, 2015; Grubert & Eimer, in press, for N2pc evidence in support of this conclusion).

The results of Irons et al. (2012) challenge claims that search templates can only represent one feature in a particular dimension at any given time (e.g., Wolfe, 2007). However, it is important to note that individual search targets used in this study were always defined by one particular feature (e.g., they were either red or green objects). If attentional templates can represent multiple target features simultaneously, how do these templates control the allocation of attention in search tasks where target objects are defined by a combination of these features? In a previous study, Kiss, Grubert, and Eimer (2013) employed spatial cueing procedures to address this question. Participants searched for targets defined by a specific colour-size combination (e.g., a small red object). Search displays were preceded by spatially uninformative cue displays that contained a singleton item that matched both, one, or none of the two target-defining features. Behaviourally, spatial cueing effects indicative of attentional capture were found for fully matching cues but not for cues that only matched one of the two target attributes, indicating that partially template-matching objects failed to attract attention. This suggests that attentional templates for conjunctively defined targets can guide attention efficiently and selectively only to objects that match all target features, without any additional allocation of attention to only partially template-matching objects. However, the pattern of N2pc results obtained in response to cue displays in the same study suggested a different interpretation. Reliable N2pc components were triggered not only by fully target-matching cues but also by partially matching cues, demonstrating that task-set contingent attentional capture was not restricted to objects with all target-defining features.

To account for the dissociation between electrophysiological and behavioural markers of attentional capture, Kiss et al. (2013) proposed that the template-guided attentional selection of conjunctively defined search targets operates in two temporally and functionally distinct stages. During an early stage that is reflected by cue-elicited N2pc components, attention is allocated to all template-matching features. During a subsequent stage, attention is then rapidly withdrawn from nontarget objects that only contain some but not all target features. The absence of behavioural spatial cueing effects for partially matching cues suggests that the de-allocation of attention from these cues is already complete when search

displays are processed. In contrast, fully matching cues produce spatial cueing effects because attention remains focused at their location during the time when the search display is processed (see also Eimer & Grubert, 2014, for further electrophysiological support for this two-stage account of attentional object selection).

In this previous experiment (Kiss et al., 2013), search targets were specified by a conjunction of features from two different dimensions (colour and size). The goal of the present study was to investigate the time course of template-guided visual search for a feature combination from the same dimension (colour). Does attentional selectivity also operate in two temporally distinct stages when observers search for targets that are defined by a specific combination of two colours? There are two different ways in which such colour-colour conjunction search targets can be specified. One possibility is to ask observers to search for objects with two target-defining colours that appear together with nontarget objects that can have one of these two target colours (*colour combination search*). Another possibility is to define search targets with respect to a specific spatial configuration of two colours (e.g., objects with a red top half and green bottom half). In such *colour configuration search* tasks, these targets can appear together with nontarget objects that have both target-defining colours, but in a different spatial configuration (e.g., green above red). Experiments 1 and 2 of the current study investigated the template-guided attentional selection of targets during colour combination search. In Experiment 3, we studied attentional control processes during colour configuration search.

In Experiment 1, participants searched for horizontally or vertically oriented target rectangles that were defined by a combination of two colours (e.g., red and green). In all search displays, a target appeared among three nontarget objects that each contained one of the two target colours (e.g., red/blue, green/brown, red/magenta). Search displays were preceded by irrelevant and spatially uninformative cue displays (Figure 1, top panel). There were three different cue display types. In "Full among No Match" cue displays, one item with both target-matching colours appeared together with three items that each had two different nontarget colours. In "Partial among No Match" displays, one of the four cue items contained one of the two target colours and was presented among three items with two nonmatching colours. In "Full among Partial" cue displays, one item with both target colours was accompanied by three other items that each matched one of the two target colours.

To assess the ability of fully and partially target-matching colour cues to attract attention during colour combination search, EEG was measured while participants performed the task, and N2pc components were computed for the three different cue display types. We

also measured spatial cueing effects as behavioural markers of task-set contingent attentional capture, separately for the different cue display types. If attention is initially allocated independently to all objects with target-matching features, but is then rapidly withdrawn from objects that only partially match a conjunctive target template, Experiment 1 should reveal similar dissociations between electrophysiological and behavioural markers of attentional capture that were previously found during search for colour/size targets (Kiss et al., 2013). Behavioural spatial cueing effects should be elicited by cue displays that contain a fully target-matching item (Full among No Match and Full among Partial displays), but not for Partial among No Match cue displays. In contrast, N2pc components should be present not just for cue displays with a fully target-matching item, but also by cue displays with one partially matching and three nontarget-colour items, demonstrating that both fully and partially target-matching colour cues are able to rapidly attract attention.

Full among Partial cue displays (where one fully target-matching item was accompanied by three partially matching items) were included in Experiment 1 to test whether attention is initially allocated independently and in parallel to multiple target-matching colours in the same display. If this was the case, both fully and partially matching cue items in these displays should attract attention and thus elicit N2pc components. Because two of the three partially matching items appear on the opposite side to the fully target-matching cue item (and thus trigger N2pc components of opposite polarity), the net N2pc elicited by Full among Partial cues should be smaller than the N2pc to Full among No Match cue displays, which include no competing partially matching items. If attention is then rapidly withdrawn from all partially matching items, the presence of these items in Full among Partial cue displays should not affect responses to subsequent search display targets. As a result, behavioural spatial cueing effects should not differ between Full among No Match and Full among Partial cue displays.

The two-stage model of attentional object selection makes very specific predictions about the pattern of electrophysiological and behavioural results in Experiment 1, and alternative scenarios are easily conceivable. For example, if the guidance of attention by colour-colour conjunction target templates was perfectly selective, only cue displays with fully target-matching items should trigger N2pc components, regardless of whether they appear among partially matching or nonmatching items, and no N2pc component should be elicited by Partial among No Match cue displays.

EXPERIMENT 1

Method

Participants

Fifteen participants were paid to take part in the study. All had normal or corrected-to-normal vision. One participant was excluded from analysis due to error rates in the task over 3 SDs from group mean. Of the remaining 14 participants, five were male and three were left-handed (mean age = 28 years, SD = 7).

Stimuli and Procedure

The experiment was created and executed using the E-Prime 2.0 software (Psychology Software Tools, Inc.), presented on a 24-inch BenQ monitor (60Hz; 1920 x 1080 screen resolution) at a viewing distance of approximately 90cm, and controlled on a SilverStone computer PC. Participants' manual responses were registered via keyboard button presses. All stimuli were presented on a black background, with a grey fixation dot (0.2° x 0.2° of visual angle) appearing constantly throughout a block. On each trial, a cue display was followed by a target display (see Figure 1, top panel). Cue displays contained four clusters of four small coloured squares that appeared in the upper left, upper right, lower left, and lower right quadrant at a distance of 1.59° from central fixation. Each cluster measured 0.64° x 0.64°, with each square measuring 0.19° x 0.19°. The four squares within each cluster always appeared in two different colours. The upper and lower square had the same colour, and the left and right squares shared another colour. Possible cue colours were red (CIE colour coordinates: .605/.322), green (.296/.604), blue (.169/.152), magenta (.270/.134), and brown (.451/.364). Target displays included four horizontally (1.8° x 0.8°) or vertically (0.8° x 1.8°) oriented rectangles that appeared at the same locations as the four cue clusters. Each rectangle was composed of two aligned equally sized squares in two different colours. The possible colours used in target displays were the same as the cue display colours. All colours were equiluminant (14 cd/m^2).

On each trial, a cue display (50 ms duration) was followed by a blank cue-target interval of 150 ms and a target display (50 ms duration). The participants' task was to search

for a rectangle composed of two pre-defined colours (e.g., red and green) in each target display, and to respond to its orientation. The specific combination of the two target-defining colours was randomised across participants. Target displays always contained one target object with both target-defining colours, and three distractor objects that had one of the two target colours and another randomly selected nontarget colour. Two of the four rectangles in the target displays were oriented vertically and the other two horizontally. For both target and distractor objects, the relative locations of the target-matching colours (above/below; left/right) varied randomly across trials. The location and orientation of the target rectangle was also selected randomly for each trial. Participants were instructed to press the '0' or '2' key on the numeric keypad with their right index and middle finger within a 1500 ms time window in response to horizontal or vertical targets, respectively. The interval between the offset of the target display and the onset of the cue display on the next trial was 1950 ms.

Target displays were preceded by one of three different types of cue displays. In "Full among No Match" cue displays, the two colours of one of the four cue items matched the two target colours (e.g., red and green, as illustrated in Figure 1, top panel), while the other three items appeared in randomly selected combinations of two nontarget colours (e.g., blue and magenta). In "Full among Partial" displays, one cue item had both target-defining colours, and the other three matched one of these colours (e.g., red and blue). In "Partial among No Match" displays, one of the cue items matched one of the two target colours, while the other three had two randomly selected nontarget colours. These three cue display types each appeared in 32 randomly interspersed trials in every block. The fully target-matching cue item or the partially matching item (in Partial among No Match cue displays) was equally likely to appear in the left or right visual field. There were two trials for each of the 16 possible combinations of matching cue location and target location for each cue type. The location of fully or partially target-matching items in these cue displays was therefore not predictive of target location in the subsequent target display. Participants completed an initial practice block of 12 trials before completing 8 experimental blocks of 96 trials.

Insert Figure 1 about here

EEG Recording and Data Analysis

EEG was DC-recorded from 27 scalp electrodes, mounted on an elastic cap at sites Fpz, F7, F8, F3, F4, Fz, FC5, FC6, T7, T8, C3, C4, Cz, CP5, CP6, P9, P10, P7, P8, P3, P4, Pz, PO7, PO8, PO9, PO10, and Oz. A 500-Hz sampling rate with a 40 Hz low-pass filter was used. Channels were referenced online to a left-earlobe electrode, and re-referenced offline to an average of both earlobes. No other filters were applied after EEG acquisition. Trials with eye-movement (exceeding ±30 µV in the HEOG channels), eye blink (exceeding ±60 µV at Fpz) and muscle movement artifacts (exceeding ±80 µV at all other channels) were rejected, as were trials with incorrect responses. The remaining trials were segmented into epochs from 100ms before prior to 500ms after cue display onset. Averaged ERP waveforms were computed for each type of cue display, separately for trials where the fully matching cue or partially matching cue (in Partial among No Match cue displays) appeared on the left or right side. N2pc amplitudes were quantified based on ERP mean amplitudes obtained between 220 and 320 ms after cue display onset at posterior electrode sites PO7 and PO8. N2pc onset latencies were determined by assessing grand averaged difference waveforms (contralateral minus ipsilateral ERPs) using a jackknife-based analysis method (Miller, Patterson & Ulrich, 1998). Fourteen subsamples of grand-averaged difference waves were computed, each excluding a different participant from the original sample. Onset latencies were determined as the point in time when each of these subsample waveforms reached an absolute threshold of -0.5 µV. They were compared between cue display types using paired t-tests with t-values corrected according to the formula described by Miller et al (1998).

Results

Behavioural Data

Reaction time (RT) data (shown in Table 1) were entered into a 3x2 repeated-measures ANOVA with the factors Cue Type (Full among No Match, Full among Partial, Partial among No Match) and Cue Validity (target at cued versus uncued location). There was a main effect of Cue Validity ($F(1,13) = 21.19.69$, $p < .001$, $\eta_p^2 = .62$), as RTs were generally faster in response to targets at cued versus uncued locations (M = 651 vs. 676 ms). Critically, a significant Cue Type x Cue Validity interaction ($F(2,26) = 28.12$, $p < .001$, $\eta_p^2 = $

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.68) demonstrated that these spatial cueing effects differed across the three types of cue displays. This is illustrated in Figure 2 (left panel), which shows spatial cueing effects (RTs to targets at cued versus uncued locations) separately for each of the three cue display types. The reliability of the spatial cueing effects triggered by each cue type was assessed with planned paired sample t-tests. Significant spatial cueing effects were present for Full among No Match cues (46 ms; $t(13) = 4.84$, $p < .001$) and Full among Partial cues (48 ms; $t(13) = 9.07$, $p < .001$). The size of these cueing effects did not differ between the two cue types ($t < 1$). In contrast, there was a reliable inverse spatial cueing effect for Partial among No Match cues (-22 ms; $t(13) = 2.45$, $p < .03$). There was also a main effect of Cue Type ($F(2,26) = 10.49$, $p < .001$, $\eta_p^2 = .45$), reflecting overall RT differences between trials where targets were preceded by Full among No Match cues, Full among Partial cues, or Partial among No Match cues (651 ms, 662 ms, and 667 ms, respectively). For error rates (shown in Table 1), there were no main effects of Cue Type ($F(2,26) = 2.15$, $p > .10$), or Cue Validity ($F(1,13) = 2.61$, $p > .10$), and no interaction between these factors ($F < 1$).

Insert Table 1 and Figure 2 about here

N2pc components to cue displays

Figure 3 (top panel) shows ERPs measured in response to the three different cue display types at electrodes PO7/8 contralateral and ipsilateral to fully target-matching cues or partially matching cues (for Partial among No Match cue displays). N2pc components appeared to be present for all three types of cue displays, but the size of these N2pcs differed between display types. This is illustrated in Figure 3 (bottom panel), which shows N2pc difference waveforms that were computed by subtracting ipsilateral from contralateral ERPs, separately for each cue type.

To assess the size of N2pc components elicited by the three different cue types, mean amplitudes obtained in the 220 to 320 ms post-stimulus time window were entered into a 3x2 repeated-measures ANOVA with the factors Cue Type (Full among No Match, Full among Partial, Partial among No Match) and Laterality (electrode ipsilateral versus contralateral to the fully or partially target-matching cue item). A main effect of Laterality ($F(1,13) = 12.74$, $p < .001$, $\eta_p^2 = .60$), reflected the presence of cue-elicited N2pc components (*M* diff = -0.78

µV). There was no main effect of Cue Type ($F(2,26) = 2.10$, $p > .10$). Importantly, a two-way interaction between Cue Type and Laterality ($F(2,26) = 13.76$, $p < .001$, $\eta_p^2 = .51$) demonstrated that N2pc amplitudes differed between the three different types of cue display (see Figure 3). Follow-up analyses conducted separately for each cue type revealed reliable N2pc components for all three types of cue displays (t's > 3.34, p's < .01). The N2pc elicited by Full among No Match cue displays was significantly larger than the N2pcs to Full among Partial displays (M diff = -1.17 vs. -.77 µV; $t(13) = 3.39$, $p < .01$) and to Partial among No Match displays (M diff = -1.17 vs. -.39 µV; $t(13) = 4.25$, $p < .01$). In addition, the N2pc triggered by Full among Partial displays tended to be larger than the N2pc in response to Partial among No Match displays ($t(13) = 2.76$, $p < .02$).

Insert Figure 3 about here

To compare the onset latency of N2pc components to Full among No Match cue displays Full among Partial displays, a jackknife-based procedure was employed, using an absolute onset criterion of -0.5 µV. Even though the N2pc emerged slightly earlier in response to Full among No Match displays, this onset latency difference was not significant (M = 225 vs. 237 ms; $t_c(13) = 2.0$, p = .067).[1]

Insert Figure 4 about here

Discussion of Experiment 1

The results of Experiment 1 provide strong support for a two stage-model of attentional object selection during visual search for conjunctively defined targets. As in an

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[1] Given the small size and gradual onset of the N2pc to Partial among No Match cue displays (see Figure 3), no reliable N2pc onset latency estimate could be computed for this cue type.

earlier spatial cueing study with colour-size targets (Kiss et al., 2013), we found a clear dissociation between electrophysiological and behavioural markers of attentional capture during search for targets defined by a colour-colour combination. Reliable N2pc components were triggered not only by Full among No Match cue displays but also by Partial among No Match cues, demonstrating that partially target-matching colour cues were able to attract attention. However, positive spatial cueing effects were only observed on trials with fully target-matching cues, whereas a reliable inverse cueing effect (i.e., faster RTs for targets at uncued locations) was present for trials with Partial among No Match cues.[2] The presence of an N2pc to Partial among No Match cues and the absence of positive behavioural spatial cueing effects in response to the same cues strongly suggest that cue-elicited N2pc components and behavioural markers of task-set contingent attentional capture are linked to different stages of attentional object selection. At an early stage that is reflected by the N2pc, attention was allocated rapidly to all cue items with target-matching colours. At a subsequent stage, attention was rapidly withdrawn from partially matching cues, but remained focused on the location of fully matching cues during the time where the search display was processed. As a result, RT benefits for targets at cued versus uncued locations were only present on trials where cue displays contained a fully target-matching item. Importantly, the size of these positive spatial cueing effects did not differ between Full among No Match and Full among Partial cue displays. In line with the two-stage account, this observation demonstrates that the presence versus absence of partially matching cue items had no impact on the distribution of spatial attention during the time when the target display was processed.

Even though behavioural spatial cueing effects were identical for Full among No Match and Full among Partial cue displays, N2pc components were smaller for the latter cue type. This suggests that all target-matching items in Full among Partial cue displays attracted attention simultaneously and independently. Because two of the three partially matching items in these displays were presented opposite to the fully target-matching item, the parallel allocation of attention to all target-matching colours will produce N2pcs of opposite polarity

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[2] Similar inverse spatial cueing effects have been observed in several previous studies in response to irrelevant-colour cues (e.g., Becker, Folk, & Remington, 2013; Carmel & Lamy, in press; Eimer et al., 2009; Lamy et al., 2004). These inverse effects might reflect spatially selective inhibition mechanisms, a perceptual mismatch between cue and target features at the same location, or object updating costs (see Carmel & Lamy, 2014, for a more detailed discussion).

in both hemispheres, resulting in an attenuated net N2pc component. If the contributions of the three partially matching items to the overall N2pc to Full among Partial cue displays were additive, the reduction of N2pc amplitudes for these displays relative to the N2pc to Full among No Match cues should correspond to the N2pc elicited by Partial among No Match cues that included a single partially matching item. To test this prediction, we compared N2pc components elicited by Full among Partial cue displays to the difference between N2pcs to Full among No Match and Partial among No Match displays. Subtracting the N2pc to Partial among No Match displays from the N2pc to Full among No Match displays produced an N2pc waveform that was very similar to the N2pc to Full among Partial displays (as shown in Figure 4). A comparison of N2pc mean amplitudes showed no significant difference between these two waveforms (-.77 vs. -.78 µV; $t < 1$). A jackknife-based procedure using an absolute criterion of 0.5 µV also showed no significant N2pc onset latency difference (237 vs. 232 ms; $t_c(13) = 1.1$, p > .25). These results show that the impact of partially target-matching cue items on N2pc components was additive, in line with the hypothesis that during the early stage of attentional object selection, attention is allocated simultaneously, independently, and in parallel to all target-matching features.

If the absence of behavioural spatial cueing effects for Partial among No Cue displays reflects the rapid de-allocation of attention from partially matching cue items, reducing the cue-target interval should make it more likely that attention is still focused at the location of these items when the target search display is processed. This prediction was tested in Experiment 2.

EXPERIMENT 2

In Experiment 2, the stimulus onset asynchrony (SOA) between the onset of cue and target arrays was reduced from 200 ms to 100 ms. Because this time interval is too short to record cue-elicited N2pc components prior to the onset of ERP activity triggered by subsequent target arrays, no EEG was recorded and only behavioural data were measured. With this shorter cue-target interval, the pattern of spatial cueing effects for target RTs should more closely reflect the spatial distribution of attention in response to the cue displays, prior to the withdrawal of attention from partially target-matching cue items (as indicated by the cue-elicited N2pc components in Experiment 1). If this was the case, positive spatial cueing effects should now also be found for Partial among No Match cue displays.

Method

Participants

Nine participants took part in Experiment 2 (4 male; *M* age = 25 years, SD = 5, all right-handed). One participant was excluded from analysis due to error rates over 3 SDs from group mean, leaving a final sample of eight. All had normal or corrected-to-normal vision and were naïve to the experimental hypotheses.

Stimuli and Procedure

The experimental set-up was identical to Experiment 1, except that the cue-target interval was reduced from 150 ms to 50 ms, and no EEG was recorded. Following practice, participants completed 6 experimental blocks of 96 trials each.

Results

RT data are shown in Table 2 and were entered into a 3x2 repeated-measures ANOVA with the factors Cue Type (Full among No Match, Full among Partial, Partial among No Match) and Cue Validity (target at cued versus uncued location). A main effect of Cue Validity ($F(1,7) = 21.37$, p < .005, $\eta_p^2 = .75$) demonstrated that RTs were generally faster for cued as compared to uncued targets ($M = 720$ vs. 786 ms). There was also a significant Cue Type x Cue Validity interaction ($F(2,14) = 13.28$, $p = .001$, $\eta_p^2 = .66$), indicating that the size of these spatial cueing effects differed between the three cue display types (as illustrated in Figure 2, middle panel). As in Experiment 1, planned comparisons of RTs to targets at cued versus uncued locations were conducted separately for the three cue display types. Significant spatial cueing effects were present on trials with Full among No Match cue displays (95 ms; $t(7) = 5.60$, $p < .001$) and trials with Full among Partial cues (69 ms; $t(7) = 4.28$, $p < .005$). In contrast to Experiment 1, reliable positive spatial cueing effects were now also found on trials with Partial among No Match cues (34 ms; $t(7) = 2.37$, $p < .05$), and spatial cueing effects were now significantly larger for trials with Full among No Match cues

relative to trials with Full among Partial cues ($t(7) = 2.83$, $p < .03$). The positive spatial cueing effect on trials with Partial among No Match cues was reliably smaller than the cueing effects for the other two cue display types (t's > 2.64, p's $< .04$). There was also a main effect of Cue Type ($F(2,14) = 4.88$, $p < .03$, $\eta_p^2 = .41$), reflecting overall RT differences between trials with Full among No Match cues, Full among Partial cues, and Partial among No Match cues (735 ms, 759 ms, and 765 ms, respectively). For error rates (shown in Table 2), there was no main effect of Cue Type ($F < 1$), Cue Validity ($F(1,7) = 3.40$, $p > .10$), and no interaction between these factors ($F(2,14) = 1.56$, $p > .20$).

Insert Table 2 about here

Discussion of Experiment 2

Reducing the SOA between cue and target arrays in Experiment 2 resulted in reliable positive spatial cueing effects on trials with Partial among No Match cue displays, indicating that attention was still focused at the location of partially matching cue items when the target display was processed. This observation supports the two-stage account of attentional object selection, as attention now had less time to withdraw from partially matching cue items prior to the perceptual analysis of target displays. The fact that spatial cueing effects were reliably smaller for Full among Partial cue displays as compared to Full among No Match cues in Experiment 2 provides additional support for this interpretation. Prior to its de-allocation from partially matching cue items, attention is not exclusively focused on the location of fully target-matching item in Full among Partial cue displays (as shown by the reduced N2pc amplitudes to these displays in Experiment 1), and this can account for the smaller spatial cueing effects produced by these displays relative to Full among No Match cue displays.

Overall, the results from Experiments 1 and 2 demonstrate that during visual search for targets defined by a colour-colour combination, attention is initially allocated independently and in parallel to all target-colour items. A more selective attentional focus that is restricted to the location of the conjunctively defined target object emerges during a second step where attention is withdrawn from objects that match only one but not both target-defining colours. If the initial stage of attentional object selection operates strictly independently for different target features within the same dimension, this stage should not be

sensitive to any relational property that is defined across these features, even when this property is task-relevant. This prediction was tested in Experiment 3.

EXPERIMENT 3

In Experiments 1 and 2, targets were defined by a combination of two colours, but the relative spatial arrangement of these two colours (e.g., red above/below green) varied randomly across trials. Experiment 3 investigated the control of attention by target templates in colour configuration search where this spatial relationship was task-relevant. Participants searched for a particular spatial configuration of two target colours (e.g., red above green). Search displays contained two types of vertically oriented objects (diamonds and capsules) with two different colours in their upper and lower halves (see Figure 1, bottom panel). In half of all trials, the target was accompanied by three nontarget objects that each contained one of the two target colours in their correct position (e.g., red above blue). In the other half, one of these nontarget objects was replaced by a "reverse-colour" nontarget that had both target colours, but in the reverse spatial arrangement (e.g., green above red). Under these circumstances, the recognition of target objects cannot be based exclusively on the presence of both two target-defining colours in the same object, but also requires the detection of the specific target-defining colour configuration. Search displays were preceded by spatially uninformative cue displays that all contained one item with target-matching features among three other items with two nontarget colours. In Full cue displays, one item had both target-defining colours in their correct spatial configuration (e.g., red above green). Partial cue displays included one item with one of the two target-matching colours in its appropriate position (e.g., red above blue). In Reverse cue displays, one item possessed both target colours, but in the opposite spatial arrangement (e.g., green above red).

If the initial allocation of attention to objects with target-matching colours, as reflected by N2pc components to cue displays, operates independently and in parallel for different target colours, this process should be entirely insensitive to the spatial configuration of these colours, even when this configuration is relevant to distinguish targets from nontarget objects. In this case, Full and Reverse cues should elicit identical N2pc components. However, if the attentional selection of conjunctively defined targets operates in two stages, attention might then be maintained only at the location of cue items with the

target-defining colour arrangement, but be rapidly withdrawn from cues where this spatial configuration is reversed. Analogous to Experiment 1, this should be reflected by reliable behavioural spatial cueing effects on trials with Full cue displays, and the absence of such effects for Reverse cues. Alternatively, the early stage of attentional object selection might already be sensitive to relational properties between target features when these properties are task-relevant. In this case, the N2pc to Reverse cues should be attenuated and/or delayed relative to the N2pc to Full cues. Partial cues were included in Experiment 3 to confirm the dissociation between electrophysiological and behavioural markers of attentional capture that was found in Experiment 1. In line with the two-stage account of attentional object selection, these cues should elicit reliable N2pc components, but no positive behavioural spatial cueing effects.

If the rapid allocation of spatial attention to candidate target objects during colour configuration search is insensitive to target-defining relational properties such as the spatial configuration of two target colours, the selection of target objects should be particularly difficult when displays also contain an object with both target colours in the opposite spatial arrangement (reverse-colour nontarget). To assess this hypothesis, we also measured N2pc components in response to target displays, separately for displays without a reverse-colour nontarget, displays where the target and a reverse-colour nontarget appeared on the same side, and displays where these two objects were presented on opposite sides. If targets and reverse-colour nontargets do not differ in their ability to attract attention, both should elicit identical N2pc components, and these two N2pcs should cancel each other out when these two objects appear on opposite sides of a target display.

Method

Participants

Fourteen participants took part in Experiment 3 (8 male; *M* age = 32 years, SD = 6, one left-handed). All had normal or corrected-to-normal vision.

Stimuli and Procedure

The experimental set-up, as illustrated in Figure 1 (bottom panel), was similar to Experiment 1, with the following exceptions. Each cluster within the cue displays now

contained only two small squares. These two squares were always vertically arranged (one above the other). The vertical spatial extent of these clusters (0.64°) was identical to Experiment 1. The two squares within each cluster always appeared in two different colours. Because the spatial arrangement of the two target-defining colours was now task-relevant, this arrangement had to be kept constant across target objects that were mapped to different responses. For this reason, the target displays now contained vertically oriented diamond-shaped or capsule-shaped objects (see Figure 1, bottom panel). The overall size and spatial arrangement of these target display objects was identical to Experiment 1. The time course of stimulus events on each trial was identical to Experiment 1, except that the interval between the offset of the target display and the onset of the cue display on the next trial was now jittered (in 100 ms steps) between 1750 and 2150 ms.

The participants' task was to detect target objects defined by a particular spatial configuration of two colours (e.g., the red above green), and to respond to its shape (diamond versus capsule). The target-defining colour combination was randomised across participants. To encourage participants to employ a search template for the specific spatial configuration of the two target colours, the target displays shown on 50% of all trials contained the target object itself, one partially target-matching nontarget object that matched the upper target colour (e.g., red above blue), another nontarget with the lower target colour, and a reverse-colour nontarget object that contained both target colours in the reverse spatial configuration (e.g., green above red). The target and the reverse-colour nontarget appeared on opposite sides on two thirds of these trials and on the same side on the remaining third. In the other 50% of all trials, the target appeared together with three partially matching nontargets. Two of these objects matched the upper target colour and one the lower target colour, or vice versa. Participants responded by pressing the '1' key for a capsule-shaped target, or the '2' key for a diamond-shaped target, on the numeric keypad with their right index and middle fingers. Each target display contained two diamond-shaped and two capsule-shaped objects.

There were three possible cue display types that all contained a single item pair with target-matching features. In Full cue displays, one item pair matched the target-defining colour configuration (e.g., red above green). In Partial cue displays, one item matched either the upper or lower target colour (e.g., red above blue or blue above green), with equal probability. In Reverse cue displays, one item pair had both target colours, but in the reverse spatial arrangement (e.g., green above red). The three other item pairs in the cue displays always had two different randomly selected nontarget colours, with the constraint that no two item pairs could be identical. After a practice block of 12 trials, participants completed 20

experimental blocks of 48 trials. Each block contained 16 randomised trials for each of the three cue display type conditions, with one trial per block for each combination of the four cue and target locations.

EEG Recording and Data Analysis

EEG recording and analysis procedures matched Experiment 1. In addition to N2pcs to cue displays, N2pc components were now also independently computed and analysed for target displays. These analyses were based on ERP waveforms averaged within a time window from 100 ms prior to cue display onset to 500 ms after target display onset, relative to a 100 ms pre-cue baseline, and across all three different cue display types. Averages were computed for search displays where a target was accompanied by three partially matching nontarget objects, displays that included the target and the reverse-colour nontarget object on the same sides, and displays where these two objects appeared on opposite sides, separately for displays with targets on the left or right side. N2pc mean amplitudes were computed at electrodes PO7/8 within a 200-300 ms time interval after target display onset. To assess longer-latency lateralised effects, additional analyses were conducted within a 300-500 ms post-stimulus time window.

Results

Behavioural Results

RTs are shown in Table 3 and were analysed in a 3x2 repeated-measures ANOVA with the factors Cue Type (Full, Reverse, Partial) and Cue Validity (target at cued versus uncued locations). There was a main effect of Cue Validity ($F(1,13) = 6.67$, $p < .03$, $\eta_p^2 = .34$), demonstrating the presence of significant spatial cueing effects ($M = 792$ vs. 770 ms). Importantly, a significant Cue Type x Cue Validity interaction was again present ($F(2,26) = 11.41$, $p < .001$, $\eta_p^2 = .47$), indicating that these cueing effects differed between the three types of cue displays (as shown in Figure 2, right panel). Planned comparisons conducted separately for each cue display type revealed significant spatial cueing effects for Full (45 ms; $t(13) = 3.85$, $p < .005$) and Reverse cue displays (29 ms; $t(13) = 2.54$, $p < .003$). The difference in the size of the effect between these two cue display conditions was significant ($t(13) = 2.41$, $p < .05$). On trials with Partial cue displays, there was a small inverse spatial

cueing effect (-9 ms) that was however not reliable ($t(13) = 1.05$, $p > .30$). The cue validity effect on these trials differed reliably from the effect observed in trials with Full and Reverse cue displays (t's > 2.95, p's $\leq .01$). There was also a main effect of Cue Type ($F(2,26) = 4.74$, $p < .02$, $\eta_p^2 = .27$), due to overall RT differences between trials with Full, Reverse, and Partial cue displays (773 ms, 780 ms, and 791 ms, respectively).

To assess whether the presence versus absence of a reverse-colour nontarget (an object with both target-defined colours in the opposite spatial configuration) in a search display affected target RTs, an additional analysis was conducted that also included the factor Reverse Nontarget (present, absent). RTs were substantially and reliably delayed when a reverse-colour nontarget was present in the same display (820 vs. 743 ms; $F(1,13) = 69.22$, $p < .001$, $\eta_p^2 = .84$). This effect did not interact with Cue Validity ($F(1,13) = 2.01$, $p > .15$) or Cue Type ($F(2,26) = 1.13$, $p > .30$), and there was no three-way interaction ($F < 1$).

Insert Table 3 about here

The analysis of error rates (shown in Table 3) revealed a main effect of Cue Type ($F(2,26) = 9.14$, $p = .001$, $\eta_p^2 = .41$), with errors more frequent on trials with Partial cue displays (12%) than for trials with Full or Reverse cues (9% and 10%; t's > 2.59, p's $< .03$). The difference in error rate between trials with Full and Reverse cues was not reliable ($t(13) = 2.06$, $p > .05$). There was no main effect of Cue Validity ($F(1,13) = 1.47$, $p > .20$) for error rates. The Cue Type x Cue Validity interaction approached significance ($F(2,26) = 3.08$, $p = .06$).

N2pc components to cue displays

Figure 5 (top panel) shows ERPs measured for Full, Reverse, and Partial cue displays types at electrodes PO7/8 contralateral and ipsilateral to a cue item that matched both or one target-defining colour. N2pc components were clearly triggered by all three types of cue displays. As can also be seen in the N2pc difference waves in Figure 5 (bottom panel), these components appear equal in size for Full and Reverse cues, and attenuated for Partial cues. Mean amplitudes obtained within the 220-320 ms post-stimulus time window were entered into a 3x2 repeated-measures ANOVA with the factors Cue Type (Full, Reverse, Partial)

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and Laterality (electrode contralateral versus ipsilateral to the target-matching cue item). There was a main effect of Laterality ($F(1,13) = 32.68$, $p < .001$, $\eta_p^2 = .72$), reflecting the presence of reliable N2pc components. A significant Cue Type x Laterality interaction ($F(2,26) = 5.71$, $p < .01$, $\eta_p^2 = .31$) suggested that the size of the N2pc differed between different types of cue displays. Analyses conducted separately for each cue display type confirmed that N2pc components were reliably triggered by all three types of cues (t's > 4.43, p's ≤ .001). The N2pcs in response to Full and Reverse cues did not differ in size (-.97 vs. -.93 μV; $t < 1$). However, both were larger than the N2pc to Partial cues (-.58 μV; t's > 2.24, p's < .05). There were no N2pc onset latency differences between trials with Full, Reverse, and Partial cue displays ($F_c < 1$).

Insert Figure 5 about here

N2pc components to target displays

Figure 6 (top panel) shows ERPs measured in response to target displays (averaged across all three cue display types) at electrodes PO7/8 contralateral and ipsilateral to the side of the target object in these displays. Separate ERPs are shown for displays where the target appeared among three partially matching nontargets, displays where the target was accompanied by a reverse-colour nontarget on the same side, and trials where the target and the reverse-colour nontarget appeared on opposite sides. An N2pc component was elicited on trials without reverse-colour nontargets, and an even larger N2pc was present on trials where the target and reverse-colour nontarget object were presented on the same side. In contrast, no N2pc appeared to be present when these two objects appeared on opposite sides. As can also be seen in the N2pc difference waves computed by subtracting ipsilateral from contralateral ERPs (Figure 6, bottom panel), an enhanced contralateral negativity remained present beyond the N2pc time window throughout the 500 ms post-stimulus measurement window. This sustained posterior contralateral negativity (SPCN) was larger for displays where a target and reverse-colour nontarget were presented on the same side than for displays without a reverse-colour nontarget, and was absent when targets and reverse-colour nontargets appeared on opposite sides.

These observations were confirmed by two 3x2 ANOVA with the factors Target Display (target and reverse-colour nontarget on same side, target and reverse-colour nontarget on opposite sides, reverse-colour nontarget absent) and Laterality, conducted separately for the N2pc and SPCN time windows (200-300 ms and 300-500 ms after target display onset, respectively). For the N2pc, there was a significant interaction between these two factors ($F(2,26) = 24.25$, $p < .001$, $\eta_p^2 = .65$), demonstrating that N2pc amplitudes differed across the three target display types. Paired-sample t-tests showed that significant N2pc components were elicited by target displays without an accompanying reverse-colour nontarget (M diff = -1.45 µV; $t(13) = 6.13$, $p < .001$) and displays where the target and reverse-colour nontarget appeared on the same side (M diff = -2.44 µV; $t(13) = 5.54$, $p < .001$), but not by displays where these two objects were located on opposite sides (M diff = -.07 µV; $t < 1$). The N2pc to displays with targets and reverse-colour nontargets on the same side was reliably larger than the N2pc to target displays without a reverse-colour nontarget ($t(13) = 3.23$, $p < .005$). An analogous pattern of results was found for the subsequent SPCN time window. There was a significant Condition x Laterality interaction ($F(2,26) = 27.24$, $p < .001$, $\eta_p^2 = .68$), as the SPCN was present for target displays without a reverse-colour nontarget (M diff = -1.38 µV; $t(13) = 6.82$, $p < .001$) and displays where the targets and reverse-colour nontarget appeared on the same side (M diff = -2.32 µV; $t(13) = 5.73$, $p < .001$), but not for target displays where the two objects appeared on opposite sides (M diff = .29 µV; $t(13) = 2.02$, $p > .05$). The SPCN amplitude for displays with targets and reverse-colour nontargets on the same side was reliably larger relative to target displays without a reverse-colour nontarget ($t(13) = 2.87$, $p < .02$).

Insert Figure 6 about here

Discussion of Experiment 3

Both Full and Partial cue displays elicited reliable N2pc components indicative of task-set contingent attentional capture in Experiment 3, but behavioural spatial cueing effects were only present on trials with Full cue displays. The presence of an N2pc to Partial cues and the absence of positive spatial cueing effects in response to these cues confirm the

dissociation between electrophysiological and behavioural markers of attentional capture found in Experiment 1, and provide further support for the claim of a two-stage model of attentional selection that attention is initially attracted by all target-defining features and is then rapidly withdrawn from partially target-matching objects. Importantly, the behavioural and electrophysiological results observed on trials with Reverse cue displays provide new insights into the limitations of attentional guidance during colour configuration search when targets are defined by the specific spatial arrangement of two colours. Full and Reverse cue displays elicited identical N2pc components, demonstrating that the early stage of spatially selective attentional processing is entirely insensitive to the spatial arrangement of two target colours, even when this relational property is task-relevant. This insensitivity to relational features is likely to reflect the fact that the initial allocation of attention to target-matching features operates in parallel and independently for different features.

If the subsequent stage of attentional selectivity where attention is de-allocated from objects with partially target-matching attributes can be based on information about feature configurations, the rapid withdrawal of attention from items with both target colours in Reverse cue displays should eliminate behavioural spatial cueing effects, analogous to what was observed for Partial cues. This was clearly not the case. Reliable behavioural spatial cueing effects were elicited on trials with Reverse cues, demonstrating that attention remained focused at the location of reverse-colour cue items during the processing of target displays. The observation that spatial cueing effects were smaller with Reverse cues relative to Full cue displays suggests that some disengagement of spatial attention may have started on some trials, but this process was clearly slower and less efficient than the rapid de-allocation of attention from partially matching cues.

The pattern of electrophysiological and behavioural spatial cueing effects obtained in Experiment 3 provides initial evidence that the guidance of attention during visual search for colour-colour conjunction targets is remarkably insensitive to information about the spatial relationship between target features. This was demonstrated even more directly by the ERPs measured in response to target displays. N2pc components were present for displays where targets appeared without a reverse-colour nontarget, and were substantially larger in response to displays where these two types of objects were presented on the same side (see Figure 6). This N2pc amplitude enhancement on same-side trials suggests that attention was allocated in parallel and independently both to targets and reverse-colour nontargets. This hypothesis was strongly supported by the observation that no N2pc component was present at all for displays where these two objects appeared on opposite sides. If attention is directed simultaneously to

two objects in opposite visual hemifields, N2pc components of opposite polarity are elicited in parallel, which cancel each other out. The absence of an N2pc for targets that were accompanied by a reverse-colour nontarget in the opposite visual field is of course entirely consistent with the fact that that identical N2pcs were elicited by Full and Reverse cue displays. Both observations demonstrate that at the stage where N2pc components are generated, attentional control processes cannot distinguish between targets and reverse-colour nontarget objects.

Importantly, this insensitivity to information about colour configuration did not only affect the rapid allocation of attention that is reflected by the N2pc, but also subsequent stages of attentional processing. As shown in Figure 6, the spatial distribution of attention that was evident during the N2pc time window remained present during the entire 500 ms interval after target display onset. In many attentional selection tasks, a sustained posterior contralateral negativity (SPCN) follows the N2pc component (e.g., Jolicoeur, Brisson, & Robitaille, 2008; Mazza, Turatto, Umiltà, & Eimer, 2007). The SPCN has been linked to the spatially selective activation of visual working memory during the identification and categorisation of selected objects (Mazza et al., 2007; see Eimer, 2014, for further discussion). The observation that SPCN components to displays that contained the target and the reverse-colour nontarget object on the same side were larger than the SPCN to target-only displays, and the fact that no SPCN was elicited at all when these two objects appeared on opposite sides, suggest that targets and reverse-colour nontargets were both attentionally maintained in working memory. These findings indicate that for at least 500 ms after search display onset, top-down control attentional processes remained unable to differentiate between target and nontarget objects on the basis of their colour configuration. The fact that target RTs were delayed by 80 ms by the simultaneous presence of a reverse-colour nontarget object is likely to be the direct result of attention being divided between these two objects at the time when targets were identified. In the context of the two-stage model of attentional selectivity, the results of Experiment 3 demonstrate that attention can be rapidly de-allocated from nontarget objects that lack one of the target-defining features, but not from objects that differ from targets only with respect to the spatial configuration of these features.

GENERAL DISCUSSION

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In the present study, we employed spatial cueing procedures to investigate the guidance of attention by search templates for multiple target colours during colour combination and colour configuration search with behavioural and electrophysiological measures. Experiment 1 demonstrated that during search for targets defined by a combination of two colours, attention is initially allocated rapidly and independently to both target-matching colours, but is then withdrawn from objects that only match one of these colours. Experiment 2 provided further support for this two-stage selection process by showing that when target displays are presented before the attentional de-allocation from partially matching cues is complete, these cues affect target processing in a spatially selective fashion. Experiment 3 investigated colour configuration search, and showed that when targets are defined by a particular spatial arrangement of two colours, attentional guidance is unable to distinguish between targets and nontarget objects with the reverse colour configuration. Both objects attracted attention equally, both were selected in parallel when they appeared together in the same target display, and both were selectively maintained in working memory. Overall, these results demonstrate that attention can be readily guided by multiple features from the same dimension, but that this type of attentional guidance becomes highly inefficient in configuration search tasks where targets and nontargets differ only with respect to the spatial relationship between these features.

We will now discuss the general implications of the current findings for cognitive and neural models of attentional control processes during visual search. The observation that during multiple-colour search, attention is initially allocated rapidly and in parallel to all objects with target-matching colours does not support the claim of the Guided Search model that attentional guidance can only be based on a single feature from a given dimension at any time (Wolfe, 1994, 2007). In line with previous behavioural and electrophysiological evidence (Irons et al., 2012; Grubert & Eimer, in press), the results of the present study suggest that search templates can represent several target colours simultaneously. At the cortical level, the activation of such colour-specific templates might be reflected by sustained changes in the activation level of neural populations that are sensitive to particular target-defining colours. Such sustained baseline shifts of neural activity have been observed during the preparation for upcoming attentional selection tasks (e.g., Chelazzi, Duncan, Miller, & Desimone, 1998; Stokes, Thompson, Nobre, & Duncan, 2009; see also Desimone & Duncan, 1995). Once a search display that includes objects with target-matching features is presented, these baseline shifts may result in a spatially selective facilitation of the processing of these features in visual cortex. Importantly, such feature-based attentional modulations can be

elicited in a spatially global fashion at multiple locations in the visual field (e.g., Martinez-Trujillo & Treue, 2004; Bichot, Rossi, & Desimone, 2005; Serences & Boynton, 2007; see also Eimer, 2014, 2015, for a more detailed discussion of links between preparatory baseline shifts and feature-based attention). The rapid allocation of attention to objects with target-matching colours, as reflected by the N2pc to cue displays in the present study, might directly reflect such spatially global feature-based attention mechanisms during search for colour combinations. In such tasks, the simultaneous representation of different target colours in a search template would be implemented by colour-selective preparatory baseline shifts that are triggered in parallel for multiple colours, and result in subsequent feature-based attentional modulations that operate independently and simultaneously for these colours.

If attention is initially deployed to all objects with target-matching features, narrowing the attentional focus to include only the conjunctively defined target object requires an additional selection process that follows the early stage of spatially global feature-based attention. The current results suggest that this process operates through the de-allocation of attention from partially target-matching nontarget objects. It should be noted that in the present study, the evidence for a rapid withdrawal of attention from such objects was purely behavioural (i.e., the absence of positive spatial cueing effects by partially matching cues on target RTs in Experiment 1 when search displays were presented 200 ms after these cues, and the presence of such effects when this interval was reduced to 100 ms in Experiment 2), and that additional electrophysiological support for the existence of such de-allocation processes is needed. A selective withdrawal of attention from partially target-matching objects may be the result of a comparison between candidate target objects and the currently active search template. Any feature mismatch between these objects and the target template will prompt attention to be de-allocated from their location. In this two-stage scenario of attentional selectivity, attentional templates have different control functions at different times during a search episode. During the preparation for search, target templates elicit a sustained bias in the activation of neurons that are sensitive to target-defining features. Once attention has been allocated to one or several objects with template-matching features, the match or mismatch between the search template and other task-relevant object features determines whether attention is maintained or withdrawn from its current location. More generally, this two-stage model assumes that the selection of target objects in visual search is a temporally extended process where task-dependent spatially selective processing biases initially emerge in parallel feature-based fashion for different objects, before they become more restricted to only include objects that fully match a current target template.

However, this template-guided gradual narrowing of focal attentional processing appears to be limited in one important respect. Although target templates can be used to discriminate between objects that do or do not possess the full set of target features, the control of attentional selectivity remains insensitive to differences in the spatial configuration of these features, even when this is a critical target-defining attribute. This was demonstrated in Experiment 3, where focal attention was found to remain divided between targets and reverse-colour nontargets for at least 500 ms after a search display was presented. This is an important observation, because it suggests that while search templates can represent multiple colours simultaneously, these colour representations remain separate, and are not combined into an integrated analog representation of the target object. If the search templates used to control the deployment of attention towards target objects were two-dimensional pictorial representations of these objects (i.e., mental images as described by Kosslyn, 1987 and Kosslyn & Thompson, 2003), they should not only specify all target-defining colours, but also their specific spatial arrangement (e.g., red above green). Because information about the spatial configuration of target features can be directly accessed in pictorial search templates at no extra cost, observers should be able to use this configural information just as readily as information about the presence versus absence of a particular feature to guide attentional allocation processes. The fact that top-down attentional control processes were found to be entirely unable to distinguish between targets and reverse nontarget objects demonstrates that this is clearly not the case. This implies either that search templates are not analog mental images of target objects, or that the configuration of individual features within such pictorial representations of target objects is not accessible to attentional guidance processes. If attention cannot be guided by information about the spatial-configural layout of target object features, even when this information is critical to find these objects, the discrimination between targets and nontargets has to take place at a subsequent post-selective processing stage.

This conclusion has implications that go beyond the special case of colour-colour configuration search. If the allocation of attention during visual search is always controlled independently by different target-defining features, the spatial configuration between features of the same object cannot be employed by attentional guidance processes. As a result, search tasks where targets are defined by such configurations should generally be difficult. This has indeed been found in search experiments where targets and distractors were composed of lines that differed in their spatial arrangement. Search for a rotated 'T' among rotated 'Ls' (Treisman & Gelade, 1980), search for a '+' among horizontal and vertical lines that match

the size and orientation of two target line segments (Treisman & Gormican, 1988), and search for the presence versus absence of an intersection between line segments of objects (Wolfe & DiMase, 2003) are all inefficient, suggesting that attention cannot be guided by this type of spatial-configural information (see also Enns & Rensink, 1990, for similar findings during search for targets defined by the spatial arrangement of two-dimensional shapes). When feature-based guidance is insufficient to discriminate between targets and distractors, additional processes are required to find target objects. One possibility is that focal attention is allocated voluntarily and sequentially to all possible target objects until the target is found. Another possibility is that attention remains divided between candidate targets, which are processed in parallel until one of them is identified as the target. In either case, the absence of configuration-based guidance will delay target localization relative to tasks where targets can be detected by parallel feature-based control processes, resulting in inefficient search.

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Table 1: Mean reaction times and percentage error rates in Experiment 1, as a function of Cue Type and Cue Validity (SD in parentheses)

	Uncued	Cued
Full Among No Match	674 (93)	628 (77)
	5 (4)	4 (4)
Full Among Partial	686 (99)	638 (90)
	7 (6)	5 (5)
Partial Among No Match	666 (94)	688 (83)
	6 (5)	7 (7)

Table 2: Mean reaction times and percentage error rates for Experiment 2, as a function of Cue Type and Cue Validity (SD in parentheses)

	Uncued	Cued
Full Among No Match	783 (117)	688 (133)
	18 (11)	14 (12)
Full Among Partial	793 (145)	724 (168)
	18 (11)	14 (11)
Partial Among No Match	782 (133)	748 (151)
	16 (11)	15 (10)

Table 3: Mean reaction times and percentage error rates in Experiment 3, as a function of Cue

Type and Cue Validity (SD in parentheses)

	Uncued	Cued
Full Cue	796 (127)	751 (130)
	11 (8)	8 (7)
Reverse Cue	794 (127)	765 (136)
	12 (8)	9 (6)
Partial Cue	786 (130)	795 (136)
	12 (8)	13 (8)

Figure captions

Figure 1: Example of display sequences (not to scale) in Experiment 1 (top panel) and Experiment 3 (bottom panel). In all experiments, target displays were preceded by spatially uninformative cue displays. In Experiment 1, the target rectangle was defined by the combination of two colours (in this example, red and green) and was accompanied by three rectangles that matched one of the two target colours. Participants had to report the orientation of the target rectangle. The four cue display items appeared at the same location as the target display objects, and each consisted of four small squares in two different colours. "Full among No Match" cue displays contained one cue item with both target-matching colours and three items with nonmatching colours. "Full among Partial" cue displays (as shown here) contained one fully target-matching item among items containing one of the two target colours. "Partial among No Match" cue displays contained one item with one of the two target colours among three nonmatching items. Experiment 2 used the same displays, but the interval between cue and target displays was reduced to 50 ms. In Experiment 3 (bottom panel), the target object was defined by a specific colour configuration (in this example, red above green), and participants reported its shape (diamond or capsule). Half of all target displays contained a nontarget object with both target colours in the opposite configuration (reverse-colour nontarget; shown here on the opposite side to target). The four cue display each consisted of two small squares in two different colours. These displays contained three nontarget colour items that appeared together with an item that matched the target colour configuration (Full cue; as shown here), an item with both target colours in the reverse configuration (Reverse cue), or an item with one of the two target colours in its correct position and one nontarget colour (Partial cue).

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Figure 2: Spatial cueing effects on target RTs measured in Experiments 1, 2, and 3. These effects were computed by subtracting RTs to targets at cued locations from RTs to targets at uncued location, separately for each cue display type.

Figure 3: Upper panel: Grand average event-related brain potentials (ERPs) obtained in Experiment 1 in response to the three cue display types in the 350 ms interval after cue onset at electrode sites PO7/PO8 contralateral and ipsilateral to the location of the main cue. Lower panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, shown separately for "Full among No Match", "Full among Partial", and "Partial among No Match" cue displays (see legend of Figure 1 for a detailed description of these three display types).

Figure 4: N2pc difference waveform for "Full among Partial" cue displays, and an N2pc double difference waveform obtained by N2pc difference waves for "Partial among No Match" cue displays from N2pc difference waves to a "Full among No Match" cue display.

Figure 5: Upper panel: Grand average event-related brain potentials (ERPs) obtained in Experiment 1 in response to the three cue display types in the 350 ms interval after cue onset at electrode sites PO7/PO8 contralateral and ipsilateral to the location of the main cue. Lower panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, shown separately for Full, Reverse, and Partial cue displays.

Figure 6: Upper panel: Grand average ERPs obtained in Experiment 3 for target displays at PO7/8 on trials where a target appeared without a reverse-colour (RC) nontarget object, trials where targets and RC nontargets appeared on the same side, and trials where

they were presented on opposite sides. ERPs are shown for the interval between cue display onset and 500 ms after target display onset, relative to a 100 ms pre-cue baseline, and were averaged across all different cue display types. The y-axis marks the onset of the target display. P1 and N1 components elicited by the cue displays are visible prior to target display onset. Lower panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, for target displays without RC nontarget, displays where targets and RC nontargets appeared on the same side, and trials where they appeared on opposite sides.

Figure 1

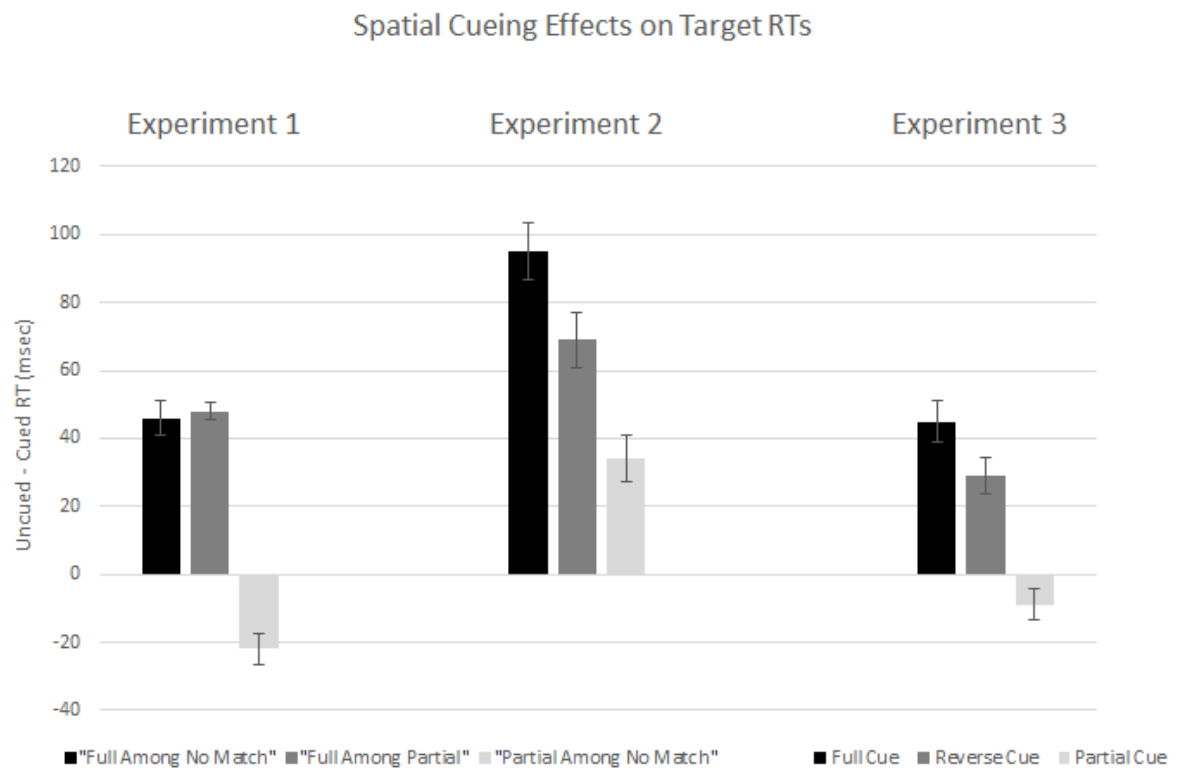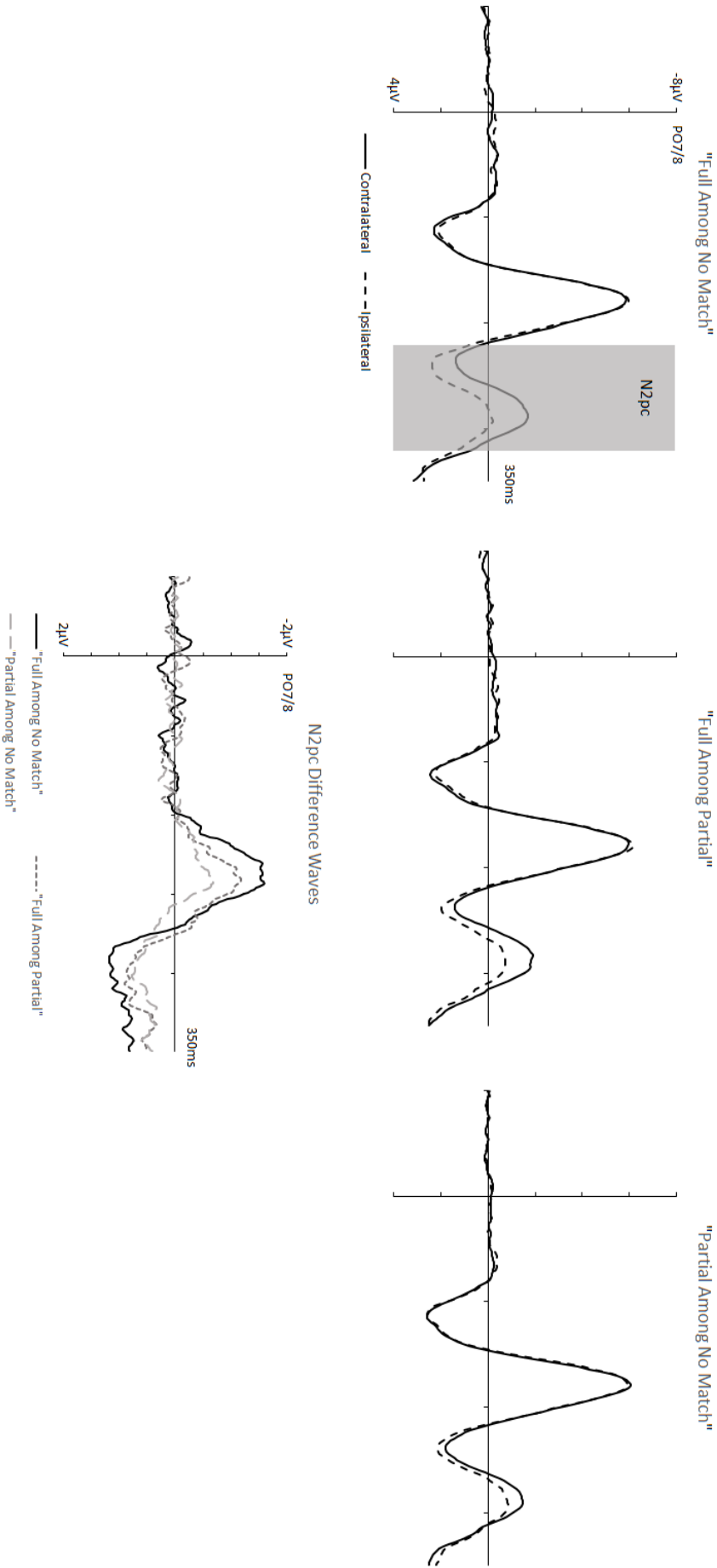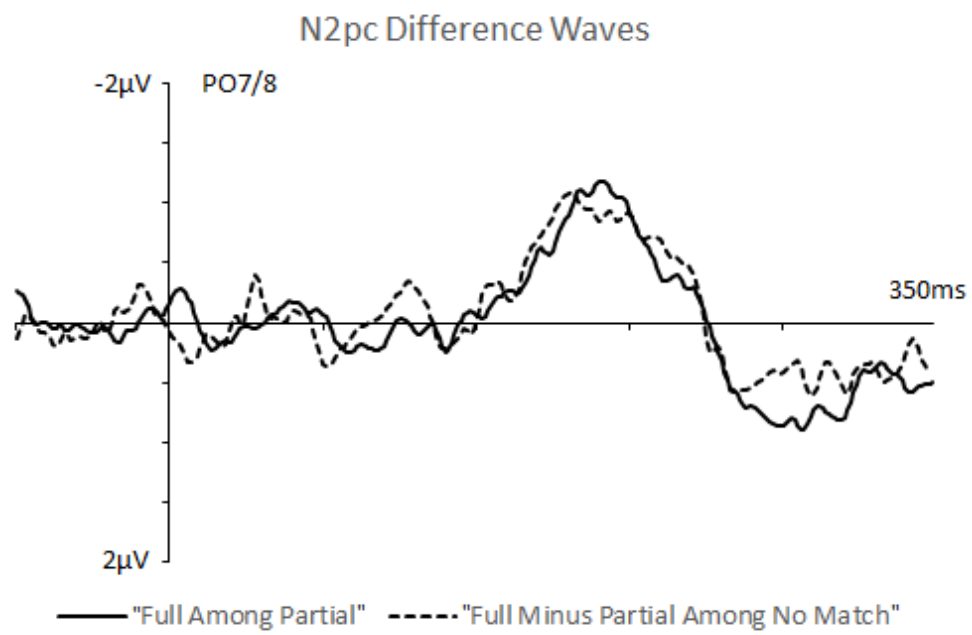Experiments 1-2
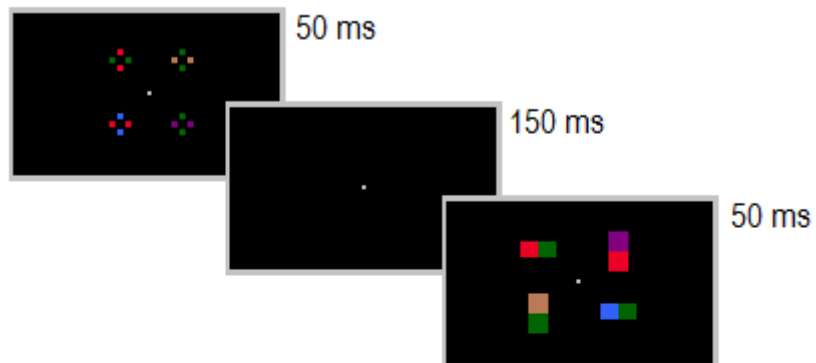
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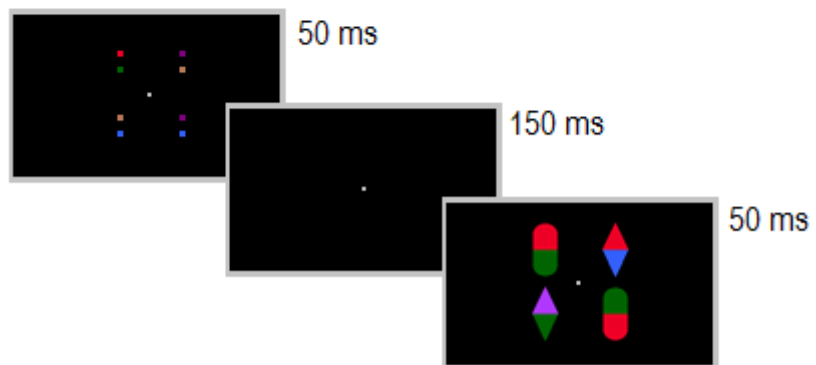
Figure 2

Figure 3

Figure 4

N2pc Difference Waves

Figure 5

Figure 6