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The spatially global control of attentional target selection in visual search

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ABSTRACT
Glyn Humphreys and his co-workers have made numerous important theoretical and empirical contributions to research on visual search. They have introduced the concept of attentional target templates and investigated the nature of these templates and how they are involved in the control of search performance. In the experiments reported here, we investigated whether feature-specific search templates for particular colours can guide target selection independently for different regions of visual space. We employed behavioural and electrophysiological markers of attentional selection in tasks with targets defined by specific colour/location combinations. In Experiment 1, participants searched for pairs of colour targets in a particular spatial configuration (e.g., red in the upper and blue in the lower visual field). In Experiment 2, they searched for single colour-defined targets at specific locations (e.g., red on the left or blue on the right). Target displays were preceded by non-informative cues containing target-colour items at task-set matching or mismatching locations. Contingent attentional capture was observed only for matching cues. However, both matching and mismatching cues elicited identical N2pc components, indicating equivalent attentional capture. This shows that the rapid deployment of attention towards target features is spatially non-selective, and that selection of colour/location combinations occurs at later post-perceptual stages. This was further corroborated in search displays where targets were accompanied by target-colour distractors at nonmatching locations. Here, spatial biases towards the target emerged late and were strongly attenuated relative to displays without such distractors. These results demonstrate that attentional templates for target-defining features operate in a spatially-global fashion. Feature-based guidance of visual search cannot be restricted to particular locations even when this is required by the demands of an attentional selection task.

How observers are able to find visual target objects that are presented at an unpredictable location together with numerous task-irrelevant distractor objects has remained one of the central issues in visual attention. In the past three decades, Glyn Humphreys and his many collaborators have made numerous important empirical and conceptual contributions to this field. Together with John Duncan, Glyn proposed a theoretical account of the factors that determine search performance that remains among the most influential models of visual search. According to their Attentional Engagement Theory (Duncan & Humphreys, 1989, 1992), search efficiency is determined by the similarity between targets and distractors and by the similarity of individual distractor objects to each other. Search is easy when targets are clearly different from distractors and all distractors are similar, and difficult under conditions where target-distractor similarity is high and distractor-

distractor similarity low. Because these two types of similarity vary gradually, search efficiency across tasks varies on a continuum, rather than reflecting a dichotomy between two qualitatively distinct parallel versus serial mechanisms of target selection, as assumed in other accounts of visual search (e.g., Treisman & Gelade, 1980). To explain how the similarity relationships between targets and distractors impacts upon search performance, Duncan and Humphreys (1992) pointed to the central role of attentional templates in the control of visual search. These templates are internal representations of the expected features of an upcoming target object that are activated prior to search, and bias the competition for spatial attention towards objects with template-matching features (see also Desimone & Duncan, 1995; Eimer, 2014, 2015; for computational models of this type of template-based guidance of visual search, see Wolfe, 1994, 2007).

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Duncan and Humphreys (1989, 1992) were among the first to highlight the importance of attentional templates in visual search. The nature of such templates and their role in the control of visual attention has since been investigated in a large number of studies with different paradigms, including numerous experiments by Glyn Humphreys and co-workers (e.g., Anderson, Heinke, & Humphreys, 2010; Hodsoll & Humphreys, 2001; Linnell & Humphreys, 2001, 2002; Quinlan & Humphreys, 1987). One important line of research on attentional templates has employed spatial cueing procedures. In these experiments, search displays containing a feature-defined target object among distractor stimuli (e.g., a red item among distractors in other nontarget colours) were preceded by task-irrelevant spatially uninformative cue displays. Cue items that matched one of the target-defining features captured attention, as reflected by faster reaction times (RTs) to subsequent targets that appeared at the same location as the matching cue as compared to targets at other uncued locations (Folk, Remington, & Johnston, 1992). In contrast, cues that did not match the currently active attentional template or top-down task set did not attract attention, even when these cues were physically salient feature singletons (Folk & Remington, 1998). Such observations have been interpreted as demonstrating that template-matching but task-irrelevant objects will capture attention in a task set-contingent involuntary fashion (e.g., Folk et al., 1992).

Event-related brain potential (ERP) studies have shown that this type of task-set contingent attentional capture is triggered rapidly at relatively early perceptual stages of visual processing (e.g., Eimer & Kiss, 2008; Eimer, Kiss, Press, & Sauter, 2009; Leblanc, Prime, & Jolicoeur, 2008; Lien, Ruthruff, Goodin, & Remington, 2008). These experiments employed analogous spatial cueing procedures to those employed in previous behavioural studies, and measured the N2pc component as an electrophysiological marker of attentional capture by template-matching cue items. 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 180–200 ms after the onset of visual arrays that contain a candidate target item, and is assumed to reflect the rapid allocation of spatial attention to these items (Eimer, 1996; Luck & Hillyard, 1994; Mazza, Turatto, Umiltà, & Eimer, 2007; Woodman & Luck, 1999). ERP studies of task-set contingent attentional capture have shown that when participants search for a specific target feature, task-set matching cues (e.g., red cues during search for red targets) trigger an N2pc, but nonmatching cues do not (e.g., red cues during search for blue targets). This demonstrates that template-matching but nominally task-irrelevant objects trigger rapid attentional capture whereas nonmatching objects do not, in line with the task-set contingent involuntary attentional capture hypothesis.

While it is generally accepted that the allocation of attention during visual search is controlled by search templates for a particular target-defining feature (see Wolfe & Horowitz, 2004, for review), the question whether such templates can represent multiple target features simultaneously is still under debate. According to Duncan and Humphreys (1992, p. 580), attentional templates specify all relevant attributes of target stimuli, and these attributes typically come from different feature dimensions (e.g., a particular combination of colour and orientation). However, can attention also be guided by search templates that represent multiple features from the same dimension (e.g., two different colours)? The fact that search for colour-colour conjunction targets (e.g., red/blue targets among blue/green and red/green distractors) is generally very inefficient (Wolfe et al., 1990) may suggest that attention can be guided by only one feature from a particular dimension at a time (e.g., Wolfe, 2007; see also Dombrowe, Donk, & Olivers, 2011; Houtkamp & Roelfsema, 2009; Menneer, Cave, & Donnelly, 2009; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011; Olivers, Peters, Houtkamp, & Roelfsema, 2011). Other results indicate that attention can be controlled by task sets for multiple target-defining colours (e.g., Beck, Hollingworth, & Luck, 2012; Moore & Weissman, 2010), and that colour/colour conjunction search can be relatively efficient (e.g., Carrasco, Ponte, Rechea, & Sampedro, 1998). Work from the Humphreys lab has suggested that pairs of colour/colour conjunction targets can be processed in parallel (Linnell & Humphreys, 2001), and that perceptual grouping of target features from the same dimension can facilitate search performance in these types of tasks (Linnell & Humphreys, 2002). Additional evidence that attentional templates can be set for

multiple colours simultaneously comes from a spatial cueing experiments by Irons, Folk, and Remington (2012) where participants had to search for one of two possible target colours, and search displays were preceded by spatially uninformative colour cues. Spatial cueing effects indicative of attentional capture were triggered by cues that matched one of the two target colours, but, critically, not by cues in a different task-irrelevant colour. This was the case even when template-matching and non-matching cue colours were not linearly separable (e.g., when participants searched for red or green targets and nonmatching cues were yellow-orange; Irons et al., 2012, Exp. 3), indicating that observers can adopt a simultaneous task set for two different target colours and exclude all other colours from this attentional template. This conclusion was supported by a recent ERP study (Grubert & Eimer, 2016) that used similar spatial cueing procedures as those by Irons et al. (2012), and found that template-matching cues triggered N2pc components during two-colour search whereas nonmatching cues did not.

If attention can be guided by simultaneous task sets for multiple colours, the question arises whether such control processes can operate independently for different locations in visual space. For example, is it possible to concurrently search for a particular colour in one visual hemifield and a different colour in the opposite hemifield? An answer to this question will have important implications for psychological and neuroscientific models of feature-guided attentional control processes. Single-unit recordings in nonhuman primates as well as from fMRI and EEG experiments in humans (Andersen, Fuchs, & Müller, 2011; Martinez-Trujillo & Treue, 2004; Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007; Zhang & Luck, 2009) have shown that when attention is directed towards a particular task-relevant feature in one hemifield, neural responses to feature-matching objects are enhanced even when these objects are located in the opposite hemifield that has to be ignored. This suggests that the allocation of attention to a particular feature at a specific location results in modulations of visual processing which spread in a global fashion across the entire visual field. The ability of template-matching objects to attract attention may be a direct consequence of the spatially global nature of feature-based attention. Activating an attentional template for a specific target feature

may result in a global bias towards template-matching objects, resulting in attentional capture by these objects irrespective of their location. If template-based attentional guidance processes always operate in such a spatially global fashion, it should generally be impossible to restrict feature-specific attentional biases to particular regions of visual space.

However, it is important to note that neural evidence for spatially global feature-based attention has typically come from tasks where human or nonhuman observers continuously monitored stimuli with task-relevant features on one side in order to detect a particular target event (e.g., a change in movement speed or direction), and no such target events occurred on the opposite unattended side. Under such conditions, spatially global feature-based attention is unlikely to interfere with task performance, and it may therefore not have been necessary for observers to adopt a more spatially localized attentional task set. A conclusive test of the question whether feature-based attention guidance can be restricted to particular task-relevant locations requires different task designs where a spatially global mode of attentional processing would impair performance, so that observers are strongly motivated to adopt task sets for particular feature/location combinations.

Recent behavioural studies that employed spatial cueing procedures have suggested that observers may indeed be able to successfully adopt separate attentional task sets for two colours at two different locations. Adamo, Pun, Pratt, and Ferber (2008) instructed participants to respond to targets defined by a specific colour/location combination (e.g., green targets on the left and blue targets on the right), and to refrain from responding when a target-colour item appeared at the incorrect location (e.g., green items on the right). Target displays were preceded by nonpredictive colour cues that either matched or did not match the target-defining colour/location conjunction. Spatial cueing effects indicative of attentional capture were only observed for spatially matching colour cues but not when these cues were presented on the opposite non-matching side. This suggests that that attentional guidance by colour templates can be restricted to specific locations in space. In a follow-up study (Adamo, Wozny, Pratt, & Ferber, 2010), the same pattern of results was found for a task where participants had to respond to shape-defined targets on one side and colour-defined targets on the other side.

While these observations indicate that location-selective attentional control for different target features is possible, they do not imply that this type of control operates at an early visual-perceptual level of attentional selectivity. In fact, the results of an N2pc study (Adamo, Pun, & Ferber, 2010) suggest that rapid attentional capture processes by target-colour items cannot be selectively restricted to particular locations in the visual field. In this study, procedures were identical to Adamo et al. (2008), except that N2pc components were measured to colour cues at matching and non-matching locations. Both types of cues elicited reliable N2pc components of similar size, indicating that both attracted attention equally. This observation is in line with the hypothesis that feature-specific attentional selection processes operate in a spatially global fashion and thus cannot be confined to specific locations (see also Parrott, Levinthal, & Franconeri, 2010; Irons & Remington, 2013; Becker, Ravizza, & Peltier, 2015, for additional behavioural support for this assumption).

However, the N2pc results by Adamo, Pun, and Ferber (2010) do not demonstrate conclusively that rapid feature-based attentional control mechanisms cannot be selectively set for particular feature/location combinations. A potential problem with the task design used in the experiments by Adamo and colleagues is that it may not have provided participants with a sufficiently strong motive to adopt such spatially selective task sets. Because search displays always contained only a single item with target-matching features, participants may have used a spatially global selection strategy, such as a feature-unspecific singleton search mode (any coloured item regardless of its value; see Bacon & Egeth, 1994) to find these candidate target objects, before making a Go/No-Go response decision at a later post-attentive processing stage (see Irons & Remington, 2013, for an analogous argument). In this case, both matching and non-matching colour cues would have attracted attention and triggered N2pc components, as was indeed observed (see also Eimer & Kiss, 2010, for N2pc evidence for attentional capture by colour cues that match the colour of a No-Go stimulus).

In summary, previous research has not yet provided a clear-cut answer to the question whether feature-based attentional guidance always operates in a spatially global fashion or can be set simultaneously for different features at different locations. To show convincingly that this type of attentional control cannot be restricted to specific task-relevant locations, search tasks are needed where participants have a strong incentive to adopt task sets for colour/location combinations, and where a failure to employ such task sets will result in costs for attentional target selection processes that can be demonstrated with behavioural and neural measures. The goal of the current study was to provide such evidence. Similar to Adamo et al. (2010), we employed spatial cueing procedures where target displays were preceded by spatially nonpredictive cue displays. Importantly, the properties of the target displays and task instructions were designed to make it impossible for participants to use a feature-unspecific singleton search mode, and encourage them to adopt a task set for particular target colour/location combinations. In Experiment 1, search displays contained two pairs of coloured bars on the left and right side (see Figure 1, top panel). The participants' task was to select one of these pairs on one side and to report whether the orientation of these two target bars was the same or different. This target pair was defined by a particular colour/location combination (e.g., a blue bar at the top and a green bar at the bottom position), and could appear with equal probability on the left or right side. In half of all trials, the two target bars were accompanied on the opposite side by two other bars in two different nontarget colours (irrelevant distractor trials). The other randomly intermixed trials were reverse distractor trials, where the target pair was presented together with two distractor bars in the two target colours, but in the incorrect spatial arrangement (e.g., green above blue). Because target and distractor pairs could not be distinguished on the basis of colour alone on these reverse distractor trials, participants had to adopt a task set for a specific configuration of two colours and two locations to locate the target pair successfully. Target displays were preceded by one of three types of cue display that all contained two differently coloured items on one side and two grey items on the other. Matching cue displays contained two target-colour items in their correct location (e.g., blue above green). In reverse cue displays, the two target-colour items appeared in the opposite spatial configuration. Neutral cue displays included two nontarget-colour items on one side. Target pairs were equally likely to appear on the same side as the preceding coloured items in the cue displays or on the opposite side, so that the cues were nonpredictive with respect to target location.
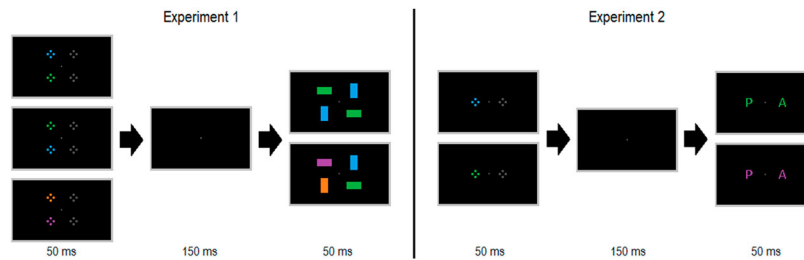
Figure 1. Example of experimental trial displays (not to scale) for Experiments 1 and 2. In Experiment 1, targets were defined as the two bars on the same side of fixation in a specific colour configuration (e.g., blue bar in the upper and green bar in the lower visual field, as shown here). Participants reported the orientation of the two target bars (same/different). The two distractor bars that accompanied the target bars on the opposite side could have the two target-defining colours in the reverse spatial configuration (e.g., green above blue; reverse distractor trials), or two different nontarget colours (irrelevant distractor trials). Target displays were preceded by spatially uninformative cue displays that contained two coloured items on one side and two grey items on the other side. Cue colours could match the target-defining colour arrangement (matching cues), appear in the reverse spatial arrangement (reverse cues), or be task-irrelevant (neutral cues; from top to bottom in Figure 1). In Experiment 2, targets were defined by a specific colour-location combination (e.g., a blue item on the left or a green item on the right) and had to be categorized as digits or letters. Each target was accompanied by a single distractor item on the opposite side that could appear in the same colour as the target (same-colour distractors) or in a nontarget colour (irrelevant distractors). Target displays were preceded by spatially uninformative cue displays that contained one item in one of the two target colours and one grey item on opposite sides. The coloured cue item could either appear on its associated task-relevant side (e.g., blue on the left; matching cues) or on the opposite task-irrelevant side (e.g., green of the left; mismatching cues).

The critical question addressed in Experiment 1 was whether participants are able to activate attentional templates for a specific target-defining colour/location configuration that can guide attention rapidly towards the location of object pairs that match this template. If this was the case, behavioural spatial cueing effects indicative of task-set contingent attentional capture should be triggered by matching cue displays, but not by reverse or neutral cues. Furthermore, only matching cue displays should trigger N2pc components contralateral to the side of the coloured cue items. No N2pc should be found for neutral cues, and critically also not for reverse cue displays, in spite of the fact that these displays contain both target colours. Such a result would demonstrate that rapid attentional capture by template-matching objects is not a spatially global phenomenon, but can be successfully prevented when target-colour objects appear at task-irrelevant locations. Alternatively, if feature-based attentional guidance operates in a spatially global fashion, reliable N2pc components should be elicited not only by matching cues, but also in response to reverse cue displays. Such a result would show that feature-matching cue items attract attention even when they are presented at irrelevant locations, and that template-guided attentional selection processes cannot be restricted to specific colour/location combinations.

In addition to recording N2pc components to cue displays, we also measured contralateral ERP modulations that were elicited in response to the subsequent target displays, separately for irrelevant distractor displays where the target pair was accompanied by two nontarget-colour items and reverse distractor displays that included two target-colour distractor items in the opposite spatial configuration. To avoid any contamination of lateralized ERP components to target displays by N2pc components elicited in response to the preceding cue displays, target ERP waveforms were collapsed across trials where coloured cue items and targets appeared on the same side and trials where these objects were presented on opposite sides. For displays where the target pair was presented together with a nontarget-colour pair on the opposite side, an N2pc should be elicited contralateral to the target pair, indicating that attention could be allocated effectively and rapidly to the target side. If attention can be guided by search templates for colour/location configurations, the attentional selection of target objects should be triggered relatively rapidly even in reverse distractor displays, in spite of the fact that two other target-colour items were present on the opposite side. This should be reflected by the presence of N2pc components to target objects in these displays, which may even be triggered at the same point in time as the target N2pc elicited by irrelevant distractor displays. In contrast, if rapid feature-based attentional guidance processes were spatially global, these processes should be unable to distinguish between the target items and the two distractor items in reverse

distractor displays, because they can only be dissociated on the basis of their colour configuration. In this case, no target N2pc will be elicited at all in response to reverse distractor displays, because both targets and reverse distractors would elicit contralateral N2pc components of similar size and opposite polarity, which cancel each other out.

The attentional processing of target objects in search displays is reflected not only by the N2pc component, but also by a subsequent sustained posterior contralateral negativity (SPCN component; Jolicœur, Brisson, & Robitaille, 2008; Mazza et al., 2007) that typically emerges around 350 ms after search display onset. While the N2pc marks the rapid deployment of attention to the location of target-matching objects, the SPCN is assumed to be linked to the spatially selective attentional activation of visual working memory representations during target identification and categorization, analogous to the contralateral delay activity (CDA) that is observed during the delay period of visual working memory tasks (e.g., Vogel & Machizawa, 2004). If target templates for colour/location configuration do not affect early attentional selection processes but only operate at later post-perceptual processing stages, a reliable SPCN might be observed for reverse distractor displays even if there was no target N2pc in response to these displays.

Experiment 1

Method

Participants

Fourteen paid participants were recruited for Experiment 1. All had normal or corrected-to-normal vision. Two participants were excluded due to a large number of rejected trials with eye-blinks and/or eye-movements (> 40% of trials). Of the remaining 12 participants, four were male and one was left-handed (mean age = 29 years, $SD = 6$).

Stimuli and procedure

The experiment was created and executed using the E-Prime 2.0 software (Psychology Software Tools, Inc.). Stimuli were presented on a 24-inch BenQ monitor (60 Hz; 1920 × 1080 screen resolution) at a viewing distance of approximately 90 cm. The

experiment was run on a SilverStone PC. Participants responded manually by pressing buttons on a regular PC keyboard. All stimuli appeared on a black background, with a grey fixation dot (0.2° × 0.2° of visual angle) constantly present throughout each block. 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). Figure 1 (left panel) shows the experimental trial sequence for all different cue and target display types. Cue displays contained four clusters of four small coloured squares that appeared in the upper left, upper right, lower left, and lower right quadrant of the visual field, with the centre of each cluster at a radial distance of 1.59° from fixation. Each cluster measured 0.64° × 0.64°, and the size of each component square was 0.19° × 0.19°. The four squares within each cluster always contained the same colours. In each cue display, the two clusters on one side appeared in two different colours, and these coloured clusters were equally likely to be presented on the left or right side. The two clusters on the opposite side appeared in grey. Possible cue colours were orange (CIE colour coordinates:.543/.409), green (.296/.604), blue (.169/.152), magenta (.270/.134), and grey (.305/.325). All colours were equiluminant (14 cd/m^2).

Target displays contained four horizontally (0.76° × 1.46°) or vertically (1.46° × 0.76°) oriented coloured rectangles that appeared at the same locations as the four clusters in the preceding cue displays. The colours used for the target displays were the same as for the cue displays, with the exception that grey never appeared in a target display. Participants were instructed to find a pair of rectangles on one side of the target display that was defined by a specific colour/location combination (e.g., the blue rectangle in the top and the green rectangle in the bottom visual field), and to report whether the orientation of this target rectangle pair was the same or different. Each participant searched for one specific target pair with a colour/location combination that remained constant across the experiment. Target-defining colour/location combinations were randomly selected for each participant. The target rectangle pair appeared equally likely and unpredictably on the left or right side. On half of all trials, the target pair was accompanied on the opposite side by a pair of rectangles in two other task-irrelevant colours (e.g.,

orange and magenta during search for blue/top—green/bottom targets; irrelevant distractor trials). On the other half of trials, the two distractor rectangles had the two target-defining colours, but in the opposite spatial arrangement (e.g., green/top—blue/bottom; reverse distractor trials). The orientation of the two distractor rectangles was randomly determined for each trial, with the exception that the four rectangles in any given target display were never allowed to all share the same orientation. As a result, trials where the spatial configuration of the target and distractor pairs was incongruent (same orientation on one side, different orientation on the other side), were more likely than congruent trials (62.5% versus 37.5%). Target displays were preceded by one of three types of cue display. In matching cue displays, the two coloured clusters on one side matched the target-defining colour/location combination (e.g., blue/top—green/bottom). In reverse cue displays, the two coloured clusters showed the two target colours in the opposite spatial arrangement (e.g., green/top—blue/bottom). Finally, neutral cue displays included two clusters in two randomly selected nontarget colours on one side. All cues were spatially uninformative, as target rectangle pair appeared on the same side as the coloured cue clusters on half of all trials, and on the opposite side on the other half.

"Same orientation" and "different orientation" responses to the target rectangle pair were made by pressing the "1" or "2" key on the numeric keypad with the right index or middle finger within a 2000 ms response window. The interval between the offset of the target display and the onset of the cue display on the next trial was randomly jittered (between 2250 and 2650 ms, in 100 ms steps). Following practice, participants completed 14 experimental blocks of 48 trials each. Each block ran through two counterbalanced sets of trials for each combination of cue display type (matching, reverse, neutral), side of coloured cue clusters (left, right), side of target rectangle pair (left, right), and target display type (irrelevant distractor trials, reverse distractor trials).

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 horizontal eye movements (exceeding ± 30 μV in the HEOG channels), eye blinks (exceeding ± 60 μV at Fpz) and muscle movement artefacts (exceeding ± 80 μV at all other channels) were removed, as were trials with incorrect manual responses. The remaining trials were segmented into epochs, separately for cue displays (from 100 ms before to 500 ms after cue display onset) and for target displays (from 100 ms prior to cue display onset to 500 ms after target display onset), relative to a 100 ms pre-cue baseline. For cue displays, averaged ERP waveforms were computed for each of the three cue conditions, separately for trials where the coloured cue clusters appeared on the left or right side of fixation. For target displays, ERPs were computed for the two target display types (irrelevant distractor and reverse distractor trials), separately for trials where the target rectangle pair appeared on the left or right side, and collapsed across trials where the coloured cue items and targets appeared on the same side or on opposite sides. For both cue and target displays, N2pc amplitudes were quantified based on ERP mean amplitudes obtained at posterior electrode sites PO7 and PO8 between 200 and 300 ms after cue or target display onset. To test whether N2pc components to target displays differed between trials where these displays were preceded by different types of cue displays, an initial analysis of N2pc mean amplitudes in response to target displays was conducted with the factors Cue Display Type (matching, reverse, neutral) and Laterality (electrode contralateral versus ipsilateral to the target). There was no evidence for an interaction between these two factors ($F(2,22) = 1.23$, $MSE = .03$, $p > .30$, $\eta_p^2 = .10$), indicating that lateralized ERP components elicited in response to target displays did not differ across the three types of cue displays. For this reason, the main analyses of target ERPs reported below were based on ERP waveforms collapsed across all three cue display types. In addition to N2pc components, SPCN components in response to target displays were also analysed. SPCN amplitudes were quantified on the basis of mean amplitudes measured between 300 and 500 ms after target display onset at electrodes PO7/PO8.

Table 1. Reaction time (upper row) and error rate (lower row) data in Experiment 1 as a function of cue condition and cue validity (standard deviation in parentheses).

	Invalid	Valid
Matching cues	769 (127)	744 (113)
	3 (3)	3 (3)
Reverse cues	775 (119)	766 (130)
	3 (3)	3 (3)
Neutral cues	751 (112)	760 (116)
	2 (3)	3 (3)

Results

Behavioural results

Cueing effects. RTs measured on trials with correct responses were entered into a 3×2 repeated-measures ANOVA with the factors Cue Display Type (matching, reverse, neutral) and Cue Validity (valid: target rectangle pair at same location as the coloured clusters in the preceding cue display; invalid: coloured cue and target pairs on opposite sides). There was no significant main effect of Cue Validity ($F(1,11) = 3.00$, $MSE = 385.15$, $p = .11$, $\eta_p^2 = .21$). However, and importantly, the interaction between Cue Display Type and Cue Validity was reliable ($F(2,22) = 4.39$, $MSE = 401.36$, $p < .05$, $\eta_p^2 = .29$). Follow-up analyses revealed that a significant spatial cueing effect was present only for trials with matching cues (M diff = 25 ms; $t(11) = 3.85$, $p < .005$). No such effect was present for trials with reverse cues (M diff = 8 ms; $t < 1$), or neutral cues (M diff = −9 ms; $t(11) = 1.24$, $p > .20$; see Table 1). There was also a main effect of Cue Display Type ($F(2,22) = 3.86$, $MSE = 442.04$, $p < .05$, $\eta_p^2 = .26$), as RTs tended to be slightly slower on trials with reverse cues. This difference was reliable when reverse-cue trials were compared to trials with neutral cues ($t(11) = 2.33$, $p = .04$), and approached significance for the comparison with matching-cue trials ($t(11) = 2.04$, $p = .066$). An analysis of error rates revealed non-significant trends for main effects of Cue Display Type ($F(2,22) = 2.75$, $MSE = 1.31$, $p = .086$, $\eta_p^2 = .20$) and Cue Validity ($F(1,11) = 3.96$, $MSE = 1.40$, $p = .072$, $\eta_p^2 = .27$), but no interaction between these two factors ($F < 1$).

Effects of target display type.

Effects of target display type. Paired-sample t-tests compared RT and error rates between irrelevant distractor trials where the target rectangle pair was accompanied by two distractors in two nontarget colours on the opposite side, and reverse distractor trials where the target pair was presented together with two target-colour distractors in the reverse

spatial configuration. RTs were substantially delayed on reverse distractor trials relative to irrelevant distractor trials ($M = 848$ vs. 676 ms; $t(11) = 9.45$, $p < .001$), whereas error rates did not differ significantly between these two types of trials ($M = 4\%$ vs. 2%; $t(11) = 1.58$, $p = .14$). To assess RT spatial cueing effects for the three different cue displays across irrelevant and reverse distractor trials, these effects were analysed with the additional factor Target Display Type (irrelevant distractor trials, reverse distractor trials). There was no three-way interaction (Cue Display Type × Cue Validity × Target Display Type: $F(2,22) = 1.16$, $MSE = 436.20$, $p > .30$, $\eta_p^2 = .10$), indicating that the pattern of spatial cueing effects for matching, reverse, and neutral cues did not differ between irrelevant and reverse distractor trials.

ERP results

N2pc components to cue displays. Figure 2 shows ERPs elicited in the 350 ms interval after cue display onset at electrodes PO7/8 contralateral and ipsilateral to the side of the coloured cue clusters, separately for the three cue display types. Clear N2pc components were elicited not only in response to matching cue displays, but also for reverse cue displays. In contrast, no N2pc was present for neutral cue displays. These observations were confirmed by an ANOVA of ERP mean amplitudes obtained between 200 and 300 ms after cue display onset with the factors Cue Display Type (matching, reverse, neutral) and Laterality (ipsilateral, contralateral). A significant main effect of Laterality ($F(1,11) = 22.20$, $MSE = .46$, $p = .001$, $\eta_p^2 = .67$) confirmed the general presence of cue-elicited N2pc components. There was also a significant Cue Display Type × Laterality interaction ($F(2,22) = 16.49$, $MSE = .15$, $p < .001$, $\eta_p^2 = .60$). To assess this interaction, N2pc difference values were computed by subtracting ipsilateral from contralateral mean amplitude values, separately for each cue display type. Reliable N2pc components were elicited by matching cues and also by reverse cues (M diff = −1.02 and −1.23 μV; ts > 4.42, ps ≤ .001). Although N2pcs were numerically larger for reverse cue displays, there was no significant N2pc amplitude difference between matching and reverse cues ($t(11) = 1.50$, $p = .16$). No N2pc was elicited by neutral cues (M diff = −.02 μV; $t < 1$). There was also a main effect of Cue Display Type ($F(2,22) = 4.14$, $MSE = .84$, $p = .03$, $\eta_p^2 = .27$), as ERP mean
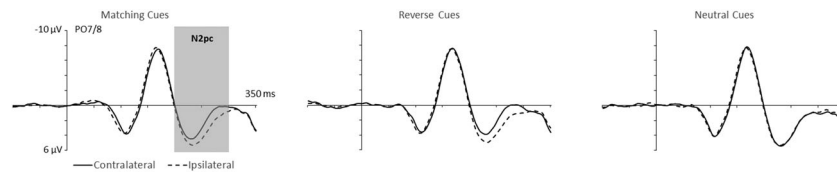
Figure 2. Grand average event-related brain potentials (ERPs) obtained in Experiment 1 in response to matching, reverse, and neutral cues in the 350 ms interval after cue onset at electrode sites PO7/PO8 contralateral and ipsilateral to the side of the coloured cue items.

amplitudes in the N2pc time window differed slightly between the three types of cues.

N2pc and SPCN components to target displays.

Figure 3 (top panels) shows ERPs elicited at PO7/8 in the interval between cue display onset and 500 ms after target display onset (relative to a 100 ms pre-cue baseline) at electrodes contralateral and ipsilateral to the side of the task-relevant rectangle pair in the target displays. These ERPs are shown separately for trials with irrelevant distractors and trials with reverse distractors (collapsed across all three cue types and colour cue locations). The corresponding difference waveforms obtained by subtracting ipsilateral from contralateral ERPs are shown in Figure 3 (bottom panel). For target displays where target rectangles were accompanied by irrelevant-colour distractors on the opposite side, a large N2pc component was followed by a substantial sustained posterior contralateral negativity (SPCN). For trials where target rectangles were presented together with a pair of distractors in the same colour but the reverse spatial configuration, no N2pc seems to have been present, and the subsequent SPCN component was strongly attenuated. These observations were confirmed by analyses of ERP mean amplitudes obtained between 200–300 ms (N2pc) and 300–500 ms (SPCN) with the factors Target Display Type (irrelevant distractor trials, reverse distractor trials) and Laterality (ipsilateral, contralateral). In the N2pc time window, there were main effects of Target Display Type ($F(1,11) = 19.76$, $MSE = .57$, $p < .001$, $\eta_p^2 = .64$) and Laterality ($F(1,11) = 33.13$, $MSE = .78$, $p < .001$, $\eta_p^2 = .75$) and, importantly, a significant interaction between these two factors ($F(1,11) = 34.02$, $MSE = .47$, $p < .001$, $\eta_p^2 = .76$). Analyses of N2pc difference waveforms confirmed that a significant N2pc component was elicited by target rectangle pairs on trials with irrelevant distractors (M diff = −2.62 µV; $t(11) = 6.56$, $p < .001$), whereas no reliable

N2pc was present on trials with reverse distractors (M diff = −.31 µV; $t(11) = 1.43$, $p = .18$). In the subsequent SPCN time window, main effects of Target Display Type ($F(1,11) = 20.05$, $MSE = 4.17$, $p = .001$, $\eta_p^2 = .65$), and Laterality ($F(1,11) = 27.18$, $MSE = 2.32$, $p < .001$, $\eta_p^2 = .71$), were again accompanied by a two-way interaction ($F(1,11) = 21.62$, $MSE = .28$, $p = .001$, $\eta_p^2 = .66$). A significant SPCN component was elicited on irrelevant distractor trials (M diff = −3.00 µV; $t(11) = 5.31$, $p < .001$). On trials with reverse distractors, this SPCN was strongly attenuated but still reliably present (M diff = −1.58 µV; $t(11) = 4.69$, $p = .001$).

Discussion of Experiment 1

The behavioural results of Experiment 1 were similar to previous findings by Adamo et al. (2010). Spatial cueing effects indicative of task-set contingent attentional capture were observed on trials with matching cue displays, but not for neutral and, importantly, also not for reverse cues. This might suggest that only matching cues were able to attract attention, whereas attentional capture by a target-colour item pair in the incorrect spatial configuration was successfully prevented. However, the ERP results obtained in Experiment 1 provide clear-cut evidence that the differential cueing effects were generated at relatively late processing stages beyond the initial rapid allocation of attention to target-colour items. Reliable N2pc components were triggered not only in response to matching cue displays, but also for reverse cues (see Figure 2). There was no N2pc amplitude difference between these two types of cue displays (with N2pcs even numerically larger in response to reverse cues), which strongly suggests that these two types of cues were equally able to capture attention in a task-set contingent fashion. Notably, no N2pc was triggered by neutral cue displays, which confirms that participants did indeed adopt a feature-specific task set for both target-defining colours. The presence of reliable N2pc
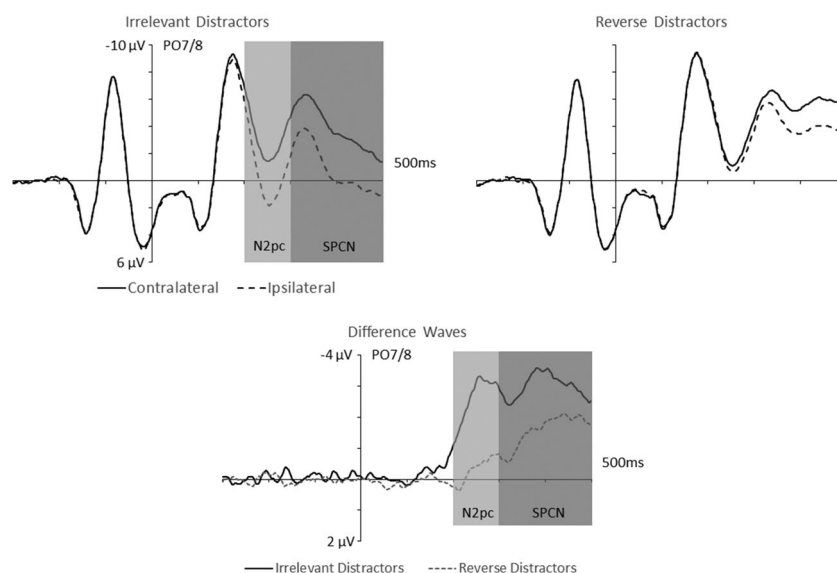
Figure 3. (Upper panel) Grand average ERPs obtained in Experiment 1 for target displays at electrode sites PO7/PO8 on irrelevant and reverse distractor trials (collapsed across all different cue display types). ERPs are shown for the interval between cue display onset and 500 ms after target search display onset, relative to a 100 ms precue baseline. The y-axis marks the onset of the target display. P1 and N1 components related to cue displays can be seen prior to target display onset. (Lower panel) Difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, shown separately for irrelevant and reverse distractor trials.

components for both matching and reverse cue displays shows that this task set initially operated in a spatially global fashion, and therefore guided attention rapidly to all target-colour items, regardless of their location. This strongly suggests that at the level at which the N2pc is generated, attentional control processes cannot be selectively tuned to particular colour/location combinations.

Additional evidence for this conclusion comes from lateralized ERP components measured at posterior electrodes in response to target displays (Figure 3). When the two target objects were presented together with two distractor items in two nontarget colours on the opposite side, marked N2pc and SPCN components were elicited contralateral to the target pair. This shows that when colour-based attentional guidance was sufficient to locate the task-relevant objects in the target displays, attention was allocated rapidly and effectively to these objects. In contrast, there was no reliable N2pc and only an attenuated SPCN component on trials where targets were accompanied by reverse target-colour distractors on the opposite side. On these trials, target selection could not rely on purely colour-based attentional guidance processes, but had to take the spatial configuration of the target-colour items into account. The observation that lateralized ERP components emerged much later and were attenuated on these

trials shows that the allocation of spatial attention to target objects was delayed and less effective. This was also reflected by the fact that target RTs were delayed by more than 150 ms for target displays with reverse distractors relative to displays with irrelevant distractors.

Overall, the ERP results obtained in Experiment 1 strongly suggest that early feature-guided attentional selection processes operate in a spatially global fashion, and are therefore insensitive to task instructions to selectively attend to particular feature/location conjunctions. In contrast, the pattern of behavioural spatial cueing effects suggests that at some later stage, attentional processes become sensitive to such conjunctions. The factors responsible for this dissociation between behavioural and electrophysiological markers of task-set contingent attentional capture will be further considered in the General discussion.

It might be argued that the task design used in Experiment 1 did not provide a fair test of the capacity to restrict feature-based attentional guidance processes to particular regions of visual space because the spatial aspect of this task was not sufficiently precise. In contrast to the study of Adamo et al. (2010), where only a single target object was presented on each trial, participants had to select two targets in two different visual field quadrants in the

current Experiment 1, and this may have reduced the effectiveness of attentional guidance by search templates for specific colour-location combinations. Previous research by Glyn Humphreys and co-workers (Hernández, Costa, & Humphreys, 2010) has shown that the size of an attentional window (narrow versus diffuse) can modulate how effectively items held in working memory are able to attract attention. In addition, the fact that the target pairs could appear with equal probability and unpredictably on the left or right side (i.e., the absence of a constant association between a particular colour and one specific location in the visual field) could have affected the utility of location-based guidance (see also Hillyard & Münte, 1984, for ERP evidence that effects of spatial attention to object locations are delayed when attended and unattended locations are difficult to discriminate). Given these design features of Experiment 1, it is possible that participants adopted a task set for a general spatial relationship between two colours (e.g., blue above green) rather than for specific colour/location combination. Colour/location search templates may still be able to guide attention, but perhaps only when a particular feature value is linked to a single constant location. This possibility was tested in Experiment 2.

Experiment 2

In Experiment 2, target displays only contained a single set of two objects (letters or digits) on opposite sides (see Figure 1, right panel). Participants had to select one of these alphanumerical items and to report whether it was a letter or digit. The target item for any given trial was defined by a specific colour/location combination (e.g., blue items on the left and green items on the right). In this task, each of the two target colours was now linked to one precisely defined task-relevant location, in contrast to Experiment 1. In half of all trials, the target item was presented together with a distractor item in a different irrelevant colour on the opposite side. In the other half, both items in the target display had the same colour. Because the target could only be selected on the basis of a specific colour/location association on these trials, participants had a strong incentive to activate spatially localized task sets for each of the two target colours at a particular location. Target displays were preceded by non-predictive bilateral cue

displays that contained one grey and one coloured item on opposite sides. The coloured item always matched one of the two target colours. They could appear at the instructed task-relevant location for this colour (matching cues) or on the opposite irrelevant side (mismatching cues). As in Experiment 1, behavioural spatial cueing effects and N2pc components were measured for both types of cue display, and lateralized ERP components were also measured in response to the two types of target display. If effective attentional guidance by task sets for colour/location combinations is possible under conditions where a particular colour is associated with one precise spatial location, only matching but not mismatching cues should trigger N2pc components in Experiment 2. Furthermore, target selection processes should be reasonably fast and efficient not only for displays where the target is presented together with a distractor in an irrelevant colour, but also for displays where both items appear in the same colour. This should be reflected by reliable N2pc components in response to both types of target display. In contrast, if the guidance of early attentional selection processes remains spatially global even when colour/location associations are fixed, the ERP results of Experiment 2 should mirror those of Experiment 1.

Method

Participants

Fifteen paid participants took part in Experiment 2. All had normal or corrected-to-normal vision. One participant was excluded due to excessive alpha activity and two were excluded due to excessive artefacts as per Experiment 1. Of the remaining 12 participants, four were male and one was left-handed (mean age = 29 years, $SD = 6$).

Stimuli and procedure

Stimuli and procedures were similar to Experiment 1, with the following exceptions. There were now only two cue clusters, appearing directly left or right of fixation, with the centre of each cluster at a distance of 1.59° from fixation. Target displays included two alphanumeric characters that were shown at the same locations as cue clusters. These characters were letters or digits (2, 4, 5, 6, 7, 8, A, G, P, Q, R, and

U) that were chosen to match items from both categories in terms of their low-level visual features (see Nako, Wu, & Eimer, 2014, for analogous procedures). All characters were matched for size (0.45° × 0.64°). The possible colours that appeared in the cue and target displays, and the time course of events on all trials, were identical to Experiment 1. Figure 1 (lower panel) shows the experimental trial sequences for the different cue and target displays used in Experiment 2. Participants' task was to identify one of the two items in the target display and to report whether this target item was a letter or a digit by pressing the "1" or "2" key on the numeric keypad with the right index or middle finger. This target item was defined by a specific colour/location combination (e.g., the blue character on the left side or the green character on the right), which was randomized across participants, and remained constant for each participant. In half of the trials, the target item on the left or right side was accompanied by a distractor item in a randomly selected nontarget colour on the opposite side (irrelevant distractor trials). In the other half, the target item was presented together with a distractor on the opposite side that had the same colour (same-colour distractor trials). The two characters on each target display were chosen randomly, but were not allowed to be identical. Furthermore, there was a mismatch between the alphanumerical categories of the target and distractor items (one letter, one digit) on 66% of all trials, and a category match (two letters or two digits) on 33% of all trials.

One of the two clusters within each cue display had one of the two target colours, while the cluster on the opposite side was grey. In matching cue displays, the side of this coloured cluster matched the target-defining colour/location combination (e.g., a blue cluster on the left when targets were blue characters on the left and green characters on the right). In mismatching cue displays, the coloured cluster appeared on the side opposite to the side assigned to this particular colour by task instructions (e.g., a blue cluster on the right when targets were blue/left and green/right items). Following practice, participants completed 10 experimental blocks of 48 trials each. Each experimental block included three counterbalanced sets of trials for each combination of cue display type (matching, mismatching), location of coloured cue cluster (left, right), target location (left, right), and target display type (irrelevant distractor trials, same-colour distractor trials).

EEG recording and data analysis

EEG recording and analysis matched Experiment 1. Averaged ERP waveforms were computed for the two cue display types, separately for trials with a coloured cue cluster on the left or right side. Averaged ERP waveforms for target displays were computed for both target display types, separately for targets on the left or right side (collapsed across trials where coloured cue items and targets appeared on the same side or on opposite sides). Analogous to Experiment 1, an initial analysis of N2pc amplitudes to target displays was conducted with the additional factor Cue Display Type (matching, mismatching). There was no interaction between this factor and the factor Laterality ($F(2,22) = 1.40$, $MSE = .07$, $p > .25$, $\eta_p^2 = .11$), indicating that target N2pc components did not differ between trials with matching and mismatching cues. Analyses of target ERPs were therefore based on ERP data that were collapsed across both cue display types.

Results

Behavioural results
Cueing effects. RTs measured on trials with correct responses were entered into a 3 × 2 repeated-measures ANOVA with the factors Cue Display Type (matching, mismatching) and Cue Validity (valid: coloured cue cluster and target at same location; invalid: coloured cue cluster and target on opposite sides). There was no effect of Cue Display Type ($F < 1$), and a non-significant trend for a main effect of Cue Validity ($F(1,11) = 3.34$, $MSE = 843.12$, $p = .095$, $\eta_p^2 = .23$). Critically, a significant two-way interaction between these two factors was present ($F(1,11) = 27.08$, $MSE = 2549.85$, $p < .001$, $\eta_p^2 = .71$). Subsequent paired-sample t-tests revealed a large and significant positive spatial cueing effect for matching cues (M diff = 91 ms; $t(11) = 4.67$, $p = .001$). For mismatching cues, a significant reverse spatial cueing effect was present (M diff = −61 ms; $t(11) = 4.46$, $p = .001$; see Table 2). There were no significant main effects or interaction for error rates (Fs < 1).

Effects of target display type. RTs were entered into a 2 × 2 repeated-measures ANOVA with the factors Target Display Type (irrelevant distractor trials, same-colour distractor trials) and Response Compatibility (compatible: target and distractor from the same

Table 2. Reaction time (upper row) and error rate (lower row) data in Experiment 2 as a function of cue condition and cue validity (standard deviation in parentheses).

	Invalid	Valid
Matching cues	1034 (127)	943 (134)
	9 (6)	9 (6)
Mismatching cues	966 (124)	1027 (114)
	9 (5)	9 (7)

alphanumerical category; incompatible: target and distractors from different categories). There was a main effect of Target Display Type ($F(1,11) = 62.17$, $MSE = 6038.81$, $p < .001$, $\eta_p^2 = .85$), with slower RTs on same-colour distractor trials relative to irrelevant distractor trials ($M = 1027$ ms vs. 895 ms). There was also a main effect of Response Compatibility ($F(1,11) = 20.33$, $MSE = 5115.08$, $p = .001$, $\eta_p^2 = .65$), as well as an interaction between both factors ($F(1,11) = 16.02$, $MSE = 5238.46$, $p < .005$, $\eta_p^2 = .59$). When the target and the distractor items had the same colour, RTs were strongly delayed on incompatible as compared to compatible trials ($M = 1160$ ms vs. 984 ms; $t(11) = 4.80$, $p = .001$). On irrelevant distractor trials, no such response compatibility effect was present ($M = 900$ ms vs. 890 ms; $t < 1$). For error rates, there was a main effect of Target Display Type ($F(1,11) = 17.16$, $MSE = 16.90$, $p < .005$, $\eta_p^2 = .61$), as errors were more frequent on same-colour distractor trials relative to irrelevant distractor trials ($M = 10\%$ vs. 6%). As for RTs, there was a main effect of Response Compatibility ($F(1,11) = 12.06$, $MSE = 35.82$, $p = .005$, $\eta_p^2 = .52$) and an interaction between both factors ($F(1,11) = 14.85$, $MSE = 18.88$, $p < .005$, $\eta_p^2 = .57$). Response compatibility affected error rates only on same-colour distractor trials ($M = 16\%$ vs. 5%, for incompatible vs. compatible trials; $t(11) = 4.17$, $p < .005$) but not on irrelevant distractor trials ($M = 6\%$ vs. 5%; $t < 1$). As in Experiment 1, an additional analysis of RT spatial cueing effects for matching and mismatching cues with the additional factor Target Display Type found no three-way interaction (Cue Display Type × Cue Validity × Target Display Type: $F < 1$), confirming that the pattern of spatial cueing effects for matching and mismatching cues did not differ between irrelevant and same-colour distractor trials.

ERP results

N2pc to cue displays. Figure 4 shows ERPs elicited in the 350 ms interval after cue display onset at electrodes PO7/8 contralateral and ipsilateral to the side of the coloured cue clusters, separately for matching and mismatching cue displays. The presence of N2pc components for the two different cue displays was assessed by an ANOVA of ERP mean amplitudes obtained in the 200–300 ms time window after cue onset, for the factors Cue Display Type (matching, mismatching) and Laterality (ipsilateral, contralateral). There was a significant main effect of Laterality ($F(1,11) = 14.34$, $MSE = .19$, $p < .005$, $\eta_p^2 = .57$), demonstrating the presence of reliable N2pc components. Follow-up analyses confirmed that significant N2pc components were elicited both by matching cue displays (M diff $= -.57$ µV; $t(11) = 4.28$, $p = .001$) and by mismatching cue displays (M diff $= -.39$ µV; $t(11) = 2.68$, $p = .02$). Although N2pc amplitudes were numerically larger for matching as compared to mismatching cues, there was no significant interaction between Laterality and Cue Display Type ($F(1,11) = 2.34$, $MSE = .04$, $p > .15$, $\eta_p^2 = .18$), indicating that N2pc components of similar size were elicited by both types of cues.

N2pc and SPCN components to target displays. Figure 5 (top panels) shows ERPs elicited at PO7/8 in the interval between cue display onset and 500 ms after target display onset (relative to a 100 ms pre-cue baseline) contralateral and ipsilateral to the side of the target item. ERPs are shown separately for irrelevant distractor trials and for same-colour distractor trials (collapsed across all types of cue displays), together with corresponding difference waveforms obtained by subtracting ipsilateral from contralateral ERPs (Figure 5, bottom panel). On irrelevant distractor trials, pronounced N2pc and SPCN components were elicited. On same-colour distractor trials, these components were strongly attenuated. These observations were assessed in ANOVAs conducted separately for the N2pc and SPCN time windows (200–300 ms and 300–500 ms after target display onset, respectively), for the factors Target Display Type (irrelevant distractor, same-colour distractor) and Laterality. In the N2pc time window, a main effect of Laterality ($F(1,11) = 59.67$, $MSE = .10$, $p < .001$, $\eta_p^2 = .84$) was accompanied by an interaction between Laterality and Target Display Type ($F(1,11) = 16.55$, $MSE = .08$, $p < .005$, $\eta_p^2 = .60$), confirming that N2pc components were larger on irrelevant distractor trials. Follow-up analyses showed a reliable N2pc on these trials (M diff $= -1.01$ µV; $t(11) = 7.76$, $p < .001$). On same-colour distractor trials, the N2pc was strongly attenuated
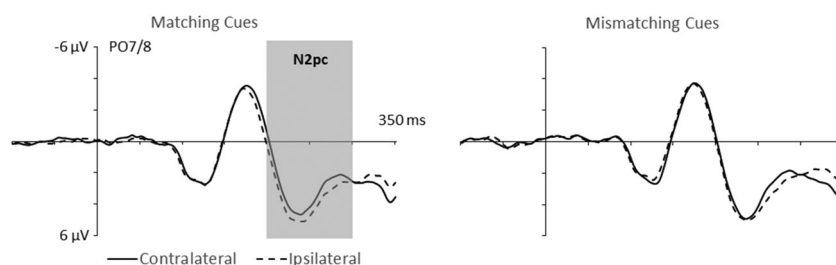
Figure 4. Grand average ERPs obtained in Experiment 2 in response to matching and mismatching cue displays in the 350 ms interval after cue onset at electrode sites PO7/PO8 contralateral and ipsilateral to the side of the coloured cue item.

but still significant (*M* diff = −.37 μV; *t*(11) = 3.43, *p* < .01). In the SPCN time-window, main effects of Target Display Type (*F*(1,11) = 20.34, *MSE* = 1.28, *p* = .001, η_p^2 = .65) and Laterality (*F*(1,11) = 40.25, *MSE* = .41, *p* < .001, η_p^2 = .79), were accompanied by an interaction between both factors (*F*(1,11) = 29.21, *MSE* = .27, *p* < .001, η_p^2 = .73). A large and reliable SPCN component was elicited on irrelevant distractor trials (*M* diff = −1.97 μV; *t*(11) = 6.18, *p* < .001). Although strongly attenuated, a significant SPCN was also present on same-colour distractor trials (*M* diff = −.37 μV; *t*(11) = 3.65, *p* < .005).

Discussion of Experiment 2

Analogous to Experiment 1, positive spatial cueing effects indicative of task-set contingent attentional capture were elicited by matching cue displays but

not by mismatching cue displays where the target-colour item appeared on the opposite task-irrelevant side. In fact, mismatching cues elicited a reverse spatial cueing effect in Experiment 2, with faster RTs to targets on the uncued side. However, and critically, both types of cues elicited reliable N2pc components, indicating that they both attracted attention. If attentional guidance could be successfully tuned to particular colour/location combinations under conditions where each colour is precisely mapped to one specific location in visual space, N2pc components should have been triggered only by matching but not by mismatching colour cues, which was clearly not the case in Experiment 2. Although N2pc amplitudes were numerically larger for matching as compared to mismatching cues, this difference was not reliable, suggesting that there were no systematic differences in the degree of attentional capture by these two
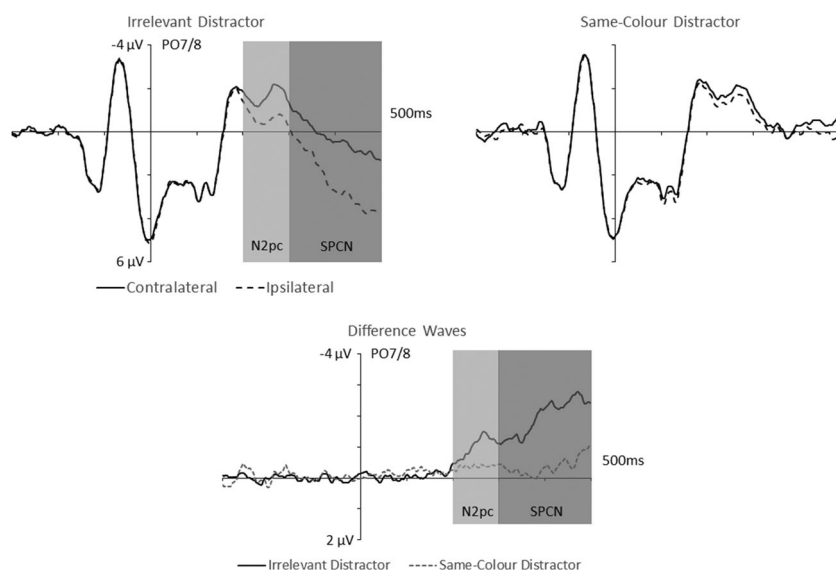

Figure 5. (Upper panel) Grand average ERPs obtained in Experiment 2 for target displays at PO7/PO8 electrode sites on irrelevant and same-colour distractor trials (collapsed across all different cue display types). ERPs are shown for the interval between cue display onset and 500 ms after target display onset, relative to a 100 ms precue baseline. (Lower panel) Difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, shown separately for irrelevant and same-colour distractor trials.

types of cues. The reverse behavioural spatial cueing effect found for mismatching cues could thus reflect a selective withdrawal of attention from the location of these cues that follows the initial attentional capture. This will be further considered in the General discussion.

As in Experiment 1, lateralized ERP components elicited in response to target displays differed considerably between displays where the target item appeared together with a distractor in a different task-irrelevant colour and displays where the distractor had the same colour as the target (Figure 5). Clear N2pc and SPCN components were elicited on irrelevant distractor trials, demonstrating that target items were selected rapidly and processed efficiently when target selection could be guided by colour. In contrast, these components were strongly attenuated on same-colour distractor trials, indicating that the allocation of attention to target items was much less efficient when it had to be based on a specific colour/location combination. In contrast to Experiment 1, where no reliable N2pc component was found at all for target displays that contained a reverse target-colour distractor pair, the target N2pc on the same-colour distractor trials of Experiment 2 was strongly attenuated, but still significant. In line with these ERP results, there were also marked behavioural differences between irrelevant-colour and same-colour distractor trials. RTs were delayed by more than 100 ms on same-colour distractor trials, and there were also strong response compatibility effects on these trials, with slower RTs when target and distractor items differed in their category than when they had the same category. The presence of compatibility effects on same-colour distractor trials and the absence of such effects on irrelevant-colour distractor trials suggests that distractor identity was processed only in the former type of trials. This is likely to directly reflect the inefficiency of attentional target selection on trials where it cannot be guided by colour alone.

General discussion

Previous behavioural and electrophysiological studies have shown that attentional task sets for two different target-defining colours can be simultaneously active (e.g., Irons et al., 2012). The goal of the present study was to find out whether specific colour search templates can be set to operate selectively for particular locations of the visual field, or whether feature-based attentional guidance always operates in a spatially global fashion. In Experiment 1, participants searched for pairs of coloured target bars defined by a specific combination of their colours and locations. In Experiment 2, the task was to report the category (letter/digit) of single items that matched a particular colour/location conjunction. To ensure that participants would adopt combined colour/location target templates in both experiments, target objects were presented together with target-colour distractors in the incorrect position on half of all trials. Target displays were preceded by nonpredictive cue displays that contained target-colour items at target-matching or nonmatching locations.

In both experiments, matching cues elicited behavioural spatial cueing effects, indicating that they attracted attention. In contrast, nonmatching cues triggered no cueing effect (in Experiment 1) or a reverse effect (in Experiment 2). The fact that only matching cues produced task-set contingent attentional capture effects may suggest that attentional templates can be set independently for specific target colours at particular locations, thereby preventing colour-matching but spatially nonmatching objects from capturing attention (see Adamo et al., 2008, for an analogous argument). However, the pattern of N2pc components elicited by cue displays that contained target-colour items at matching or nonmatching locations suggest that such a conclusion would be incorrect. In both experiments, reliable N2pc components were triggered not only by both matching cues but also by nonmatching cues. This demonstrates that target-colour cue items captured attention not only when they appeared at target-defining locations, but also when they were presented at other task-irrelevant locations. In Experiment 1, N2pc components were even numerically larger for nonmatching as compared to matching cues. In Experiment 2, the opposite tendency was found, with larger N2pc amplitudes for target-colour cues at target matching locations. Although this numerical tendency was not significant, its presence in Experiment 2 makes it difficult to completely rule out the possibility that the ability of target-colour cues to attract attention can be modulated by whether these cues appear at task-relevant or irrelevant locations. However, and most importantly, the current N2pc results clearly show that attentional capture contingent on colour-specific task sets cannot be restricted to specific locations in the visual field.

A similar dissociation between behavioural and ERP markers of task-set contingent attentional capture has been found in two previous studies from our lab where participants searched for targets defined by feature conjunctions (e.g., a particular colour and size, or a combination of two colours), and target displays were preceded by cue displays that contained fully or partially target-matching items (Berggren & Eimer, 2016; Kiss, Grubert, & Eimer, 2013). Behavioural spatial cueing effects were elicited by fully matching cues but not by cues that only had one of the two target-defining features. However, these partially matching cues triggered reliable N2pc components, indicating that they captured attention. To account for this dissociation, we suggested that attention is initially allocated to all objects with target-matching features, but is then withdrawn from objects that share some but not all features with the current target. An analogous hypothesis may explain the fact that target-colour cues at mismatching locations elicited significant N2pc components but no positive spatial cueing effects in the present study. During the early stage of attentional selection where the N2pc is generated, all items that match one of the current target colours attract attention equally, regardless of their location in the visual field. During a later stage, attention is withdrawn from target-colour cues that do not match a particular target-defining colour/location combination, which eliminates any facilitation of RTs to subsequent target objects that appear at the location of these cues. The presence of inverse spatial cueing effects for mismatching target-colour cue items observed in Experiment 2 but not in Experiment 1 (see also Belopolsky, Schreij, & Theeuwes, 2010; Anderson & Folk, 2012, for similar observations) may be due to the fact that mismatching cue displays only contained a single target-colour item in Experiment 2 but two such items in Experiment 1. The withdrawal of attention from a single task-irrelevant location could result in the selective inhibition of this location, whereas less location-specific inhibition may be elicited when attention is initially captured by two target-colour items at two different location (see Carmel & Lamy, 2014, for an alternative account of such inverse cueing effects).[1]

The pattern of lateralized ERP components elicited in response to target displays provides additional evidence for marked limitations in the ability of target templates for colour/location combinations to guide spatial attention. In both experiments, target objects elicited large N2pc and SPCN components when they were accompanied by nontarget-colour distractors in the same display, and target selection could therefore be entirely controlled by colour. The emergence of an N2pc at around 200 ms after target display onset shows that attention was allocated rapidly to target objects on these trials. However, when colour targets were presented together with distractor items that appeared in the same colours but at mismatching locations, and target selection therefore had to be based on colour/location conjunctions, these lateralized components were strongly reduced in size. No reliable N2pc was elicited at all in Experiment 1, and N2pc components were strongly attenuated albeit still significantly present in Experiment 2. This demonstrates that the rapid deployment of attention to target objects was strongly impaired on these same-colour distractor trials. The subsequent SPCN component was reliably present on these trials in both experiments, indicating that target templates for colour/location combination can affect attentional processing at later post-perceptual stages. However, SPCN amplitudes were much smaller relative to trials with irrelevant-colour distractors, which suggests that even at post-perceptual levels the spatially selective processing of target objects remained inefficient.

These N2pc and SPCN differences between the two different types of target display directly reflect the increased difficulty of guiding attentional processes on the basis of colour/location conjunctions as compared to purely colour-based attentional guidance. When the allocation of attention has to be controlled by task sets for a specific colour/location combination, spatially selective attentional biases emerge later and are less pronounced relative to situations where target selection is controlled by colour only. The marked attenuation of N2pc and SPCN components to target displays on these same-colour distractor trials suggests that spatial attention remained partially divided between target and distractor objects, which

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[1]The presence versus absence of a colour change between cue and target displays may also have contributed to the pattern of behavioural spatial cueing effects in Experiment 2. Trials with fast RTs (valid trials with matching cues and invalid trials with mismatching cues) were trials where the cues and targets had the same colour, whereas RTs were slow on trials where there was a colour change. The reverse spatial cueing effect observed for trials with mismatching cues (and the large positive spatial cueing effects on trials with matching cues) may therefore in part also reflect RT costs associated with a colour change.

can also account for the presence of response compatibility effects on these trials but not on irrelevant-colour distractor trials in Experiment 2.[2] If task sets for colour/location combinations primarily operate at relatively late stages that follow the initial allocation of attention to all target-colour objects, it may primarily affect attentional processes beyond the perceptual processing of visual input. In the present study, where target displays were only presented for 50 ms, such task sets will therefore not modulate the on-line sensory encoding of these displays, but only their subsequent maintenance in visual working memory. This is in line with the observation that reliable albeit small SPCN components were elicited in both experiments in response to target displays that included same-colour distractor objects. As the SPCN is regarded as a neural marker of the spatially selective retention of visual stimulus representations in working memory (e.g., Mazza et al., 2007), this result suggests that attentional templates for colour/location combinations primarily affect the post-perceptual storage and processing of visual information in a short-term working memory store. This late stage of attentional processing in working memory has been proposed to be responsible for the identification of a visual object that is based on the combination and integration of individual features (see Eimer, 2014, 2015). The current results suggest the conjunction of features and locations and the spatial configuration of different features may only become fully available once stimuli have been encoded into working memory.

The attenuation and delay of spatially selective attentional biases for displays where target objects and distractors had to be distinguished on the basis of task sets for colour/location conjunctions observed in the present study is consistent with observations from a recent ERP experiment on colour/colour conjunction search (Berggren & Eimer, 2016, Exp. 3), where participants searched for target objects that had two specific colours in a particular spatial configuration (e.g., red above green). In some search displays, the target object was accompanied on the other side by a distractor object with the same two target colours in the opposite spatial configuration (e.g., green above red). On these trials, no N2pc or SPCN components were elicited contralateral to the side of the target object, indicating

that, for the first 500 ms after target display onset, attentional guidance processes were unable to differentiate between target and distractor objects on the basis of their colour configuration. This finding underlines the primacy of spatially non-selective feature-based control processes in the allocation of attention during visual search. In line with the current study, it suggests that early stages of attentional selectivity cannot be efficiently guided by information about the spatial-configural properties of target features, even when this information is necessary to find target objects (see also Irons & Remington, 2013, for additional behavioural evidence that attentional task settings for colour/location conjunctions operate at late stages of visual processing).

In summary, the present study has provided new electrophysiological insights into the nature of attentional templates and into how these templates control the allocation of spatial attention during visual search. In their seminal article, Duncan and Humphreys (1992) assumed that attentional templates specify all relevant attributes of target stimuli. The current findings show that even though this may be the case for non-spatial target features, templates for particular feature/location combinations cannot restrict the initial rapid guidance of attentional target selection during visual search. Feature-specific target templates cannot be restricted to particular regions of visual space, even when this is required by the demands of a specific selection task. Our results suggest that feature-guided attentional target selection operates in a spatially global fashion, and is therefore strongly impaired when tasked with distinguishing between target features at task-relevant and irrelevant locations. This conclusion has more general implications for the nature of attentional control in visual search (see Eimer, 2014, 2015, for more detailed discussion). In a typical search task, observers look for a particular object with known target-defining features at unpredictable locations. Because target location is unknown, feature-based attentional control processes have to operate in a spatially non-selective fashion across all possible target locations, in order to guide attention towards objects with target-matching features, regardless of their location. As a result of

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[2]It should be noted that there was no main effect of Response Compatibility and no interaction between Response Compatibility and Target Display Type in Experiment 1 (both $F < 1.6$). This difference is presumably because responses were determined by the properties of single objects (their alphanumerical category) in Experiment 2, but depended on a relational property between two different objects (same versus different bar orientation) in Experiment 1.

such feature-based guidance mechanisms, attention is allocated to candidate target objects. At the neural level, this is reflected by spatially selective modulations of visual activity at particular locations within retinotopic visual cortical areas, which give rise to N2pc components at the scalp surface. The current study has shown that these feature-specific attentional allocation processes cannot be confined to particular locations in the visual field, which is of course entirely in line with the idea that they are guided by spatially global mechanisms. For this reason, task sets for specific feature/location combinations primarily affect later stages of attentional processing that are involved in the identification and classification of attended stimuli and their encoding and retention in working memory.

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