



Feature-guided attentional capture cannot be prevented by spatial filtering

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ABSTRACT

Feature-based control processes guide attention towards objects with target features in visual search. While these processes are assumed to operate globally across the entire visual field, it remains controversial whether target-matching objects at task-irrelevant locations can be excluded from attentional selection, especially when spatial attention is already narrowly focused elsewhere. We investigated whether probe stimuli at irrelevant lateral locations capture attention when they precede search displays where targets are defined either by a specific feature (colour or orientation) or by a colour/orientation conjunction by measuring N2pc components (an electrophysiological marker of attentional target selection) to these probes. Reliable N2pc were triggered by probes not only in the feature search tasks but also when participants searched for feature conjunctions, in spite of the fact that conjunction search requires focal spatial attention. Analogous N2pc results were found in the absence of any spatial uncertainty about the location of conjunctively defined targets, which always appeared at fixation. These results show that rapid attentional capture by objects with target-matching features cannot be prevented by top-down spatial filtering mechanisms, and confirm that feature-based attentional guidance processes operate in a spatially global fashion.

1. Introduction

During visual search, representations of target-defining features control the allocation of attention to possible target objects (Wolfe, 1994, 2007). Such representations that can be activated prior to the start of a particular search episode have been described as attentional templates (Duncan & Humphreys, 1992) or top-down task-sets (Folk, Remington, & Johnston, 1992). These templates bias the competition between objects in search displays towards those with template-matching features and facilitate their attentional selection.

In typical search tasks, observers have information about features of the looked-for target object, but the location of this object among distractor items is unpredictable. Under such conditions, template-guided attentional control processes have to operate in a spatially global fashion across all possible target locations in the visual field. These guidance processes are likely to be implemented by mechanisms of feature-based attention. Previous neuroimaging studies in humans and non-human primates have shown that when attention is directed towards specific task-relevant features of objects at one particular location, processing biases in favour of this feature emerge simultaneously at other unattended locations, and even in the opposite hemifield (e.g., Martinez-Trujillo & Treue, 2004; Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007; Berggren, Jenkins, McCants, & Eimer, 2017). Given their spatially global nature, the biases produced by

feature-based attention might act as guidance signals during visual search, resulting in the allocation of spatial attention to objects with target-matching features (see Bichot, Rossi, & Desimone, 2005; Eimer, 2014, 2015, for further discussion).

A potential problem with feature-based spatially global guidance of attentional selection processes arises in situations when particular locations in the visual field have to be ignored. Do objects with features that match the current target template always attract attention regardless of where they appear in the visual field, or can this type of feature-based attentional capture be prevented at locations that are known to be task-irrelevant? Previous studies with informative spatial precues have shown that abrupt onset stimuli and colour singletons fail to attract attention when they appear at uncued locations that can be ignored (Yantis & Jonides, 1990; Theeuwes, 1991). They demonstrate that spatial filtering mechanisms can prevent attentional capture by salient visual objects. However, this conclusion might not apply to feature-based attentional selection processes that are controlled by specific target templates. A series of studies has found evidence that attention is attracted by all objects with template-matching features, even when they appear at irrelevant locations (Folk, Leber, & Egeth, 2002; Leblanc, Prime, & Jolicoeur, 2008; Leonard, Balestreri, & Luck, 2015). In all of these studies, participants monitored a central rapid serial visual presentation (RSVP) stream for occasional colour-defined targets. Task-irrelevant peripheral distractors that appeared prior to the

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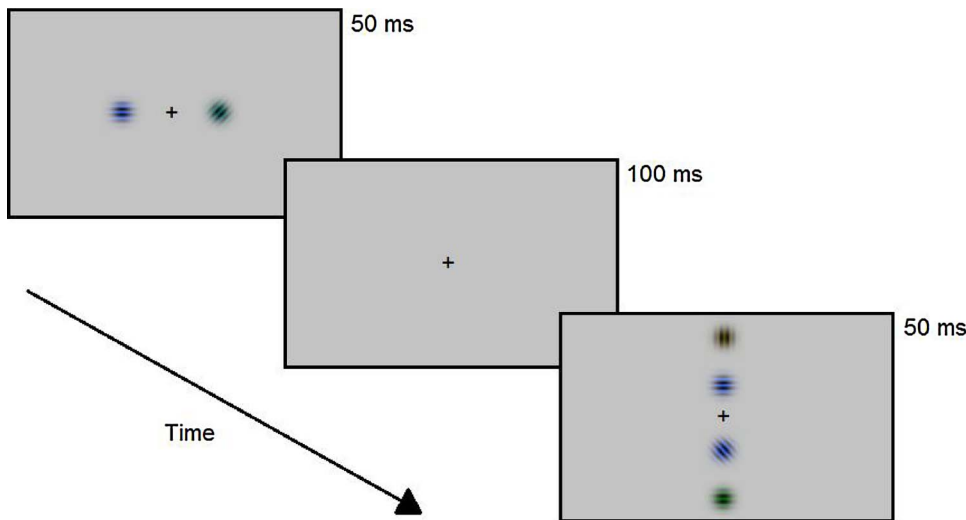


Fig. 1. Example trial display (not to scale) in Experiment 1. On each trial, a bilateral probe display was followed by a search display consisting of four objects on the vertical midline. The search display target was defined by a particular feature (colour and orientation search tasks) or a colour/orientation combination (conjunction search task). One item in the probe display always had one or both target features. The example shows a conjunction search trial where the target is the blue Gabor patch with horizontal lines, and the left Gabor patch in the probe display matched both target features. Participants' task was to report the presence or absence of the target in the search display. In Experiment 2 (not shown here), the four-item search display was replaced by a display with a single item that always appeared at fixation.

target impaired detection of the central target object when they matched the current target colour, suggesting that these template-matching distractors were able to attract attention. This was confirmed by [Leblanc et al. \(2008\)](#), who recorded event-related potentials (ERPs) during task performance and measured the N2pc component in response to distractors preceding the target in the central RSVP stream. The N2pc is an enhanced negativity that is triggered at posterior scalp electrodes contralateral to candidate target objects that are presented among distractor objects in visual search displays. This component typically emerges between 180 ms and 200 ms after search display onset and is assumed to reflect the rapid allocation of spatial attention to objects with template-matching features (e.g., [Luck & Hillyard, 1994](#); [Eimer, 1996](#); [Mazza, Turatto, Umiltà, & Eimer, 2007](#); [Eimer & Kiss, 2008](#)). In the study by [Leblanc et al. \(2008\)](#), N2pc components were triggered by distractors that matched the current target colour but not by nonmatching distractors, demonstrating that template-matching distractors attracted attention in spite of the fact that they were presented at task-irrelevant locations.

The results of these three earlier studies suggest that feature-based attentional control might indeed operate in a strictly spatially global fashion and cannot be prevented by spatial filtering processes (but see [Leonard et al., 2015](#), for evidence that feature-based attentional capture depends on the distance from the attended location). Since these studies used essentially the same paradigm with colour-defined targets appearing among distractors in an RSVP stream at fixation, these findings may be specific to this particular task context. There are two reasons why this could be the case. In contrast to typical visual search tasks, where the presentation of search displays is a discrete event and search displays usually include a target and/or partially target-matching nontarget objects, RSVP tasks require observers to sequentially scan successive single-item displays across an extended period of time, and only very few of these displays contain a target. For these reasons, spatial attention and feature-based target selection mechanisms might interact in different ways in search tasks and in RSVP tasks, which would make it problematic to draw general conclusions about the nature of these links from RSVP experiments alone (see also [Folk et al., 2002](#), for a similar caveat). Second, the discrimination between targets and nontargets in the RSVP stream in these previous studies was always very easy, as target objects were defined by a specific colour that was not shared by any of the nontargets. In visual search, selecting such unique colour-defined targets is fast and efficient and is often assumed to take place on the basis of pre-attentively available information, without the involvement of focal spatial attention (e.g., [Treisman & Gelade, 1980](#)). During the detection of colour-defined targets in RSVP streams, spatial attention may have remained relatively unfocused,

which could have allowed peripheral target-colour distractors to capture attention. If this is the case, template-matching distractors at irrelevant locations should be less likely to attract attention in tasks where the discrimination between targets and nontargets is more difficult and observers therefore have to adopt a narrow focus of spatial attention (see also [Carmel, Thorne, Rees, & Lavie, 2011](#), for evidence that increasing the attentional load of a central task reduces visual sensitivity to peripheral stimuli).

The paradigmatic case of such a demanding selection task is visual search for targets that are defined by a conjunction of features in search displays with distractor objects that also share one of these features. According to Feature Integration Theory (e.g., [Treisman, 1988](#)), detecting and identifying target objects in such conjunction search tasks requires serial movements of attention between possible target objects in a search display, because focal attention is needed to combine different features of the same object. If this was the case, top-down spatial filtering mechanisms should be strongly activated in a conjunction search task where target objects appear at particular task-relevant locations and objects at other locations have to be ignored, in order to prevent any attentional distraction by target-matching objects at irrelevant locations. Because search for targets defined by a single feature does not require focal-spatial attention to the same degree, these spatial filtering processes may not be active in feature search tasks. Thus, attentional capture by objects with target-matching features at irrelevant locations should be strongly attenuated or absent during conjunction search but not during feature search.

These predictions were tested in the current study. Our design logic was similar to previous experiments investigating task-set contingent attentional capture at irrelevant locations. Participants had to select pre-defined target objects that appeared among distractors (in Experiment 1) on the vertical midline. Target displays were preceded by bilateral probe stimuli at task-irrelevant locations in the left and right visual field and could contain target-matching features, but had to be ignored. All stimuli in the probe and target displays were Gabor patches in one of four colours and with one of four possible grating orientations (see [Fig. 1](#)). The present study differed in two critical aspects from previous experiments. First, instead of being embedded within a central RSVP stream, targets always appeared in a single search display. Second, targets were not always defined by a single feature. Instead, we directly contrasted the ability of task-irrelevant peripheral objects with target-matching features to attract attention between a task condition where target objects were specified by a unique feature and another condition where targets were defined by a feature conjunction. To assess the ability of lateral probes with target-matching features to attract attention, EEG was recorded during task

performance, and N2pc components were computed in response to these probes.

In Experiment 1, the task-relevant display on the vertical midline contained four Gabor patches, and participants reported the presence or absence of a target among these patches. There were two feature-based search tasks where the target was defined either by a specific colour or a specific orientation. On each trial, one of the two lateral probe patches matched this target feature. Unless attentional capture by target-matching features at unattended locations is restricted to the specific context of RSVP tasks (see above), probes with the target colour and target orientation should be able to attract attention in these colour and orientation search tasks, and should therefore elicit reliable N2pc components. Critically, there was also a conjunction search task, where targets were defined by a specific combination of colour and orientation, and were accompanied by one colour-matching and one orientation-matching nontarget object in the same display. In this task, one of the two probe patches matched either the target colour, its orientation, or both of these features. If task-set contingent attentional capture does not occur at task-irrelevant locations in a conjunction search task that requires a narrow focus of spatial attention, these target-matching probes should not trigger any N2pc components in this task. Alternatively, if spatially global feature-based attention operates independently of attentional processing demands at task-relevant locations, target-matching probes should trigger N2pc components not only during feature search but also in the conjunction search task.

2. Experiment 1

2.1. Method

2.1.1. Participants

Thirteen participants were recruited for Experiment 1. One participant was excluded due to over 50% data loss from artifact rejection. The remaining 12 participants (M age = 29 years; $SD = 6$, 6 male, 1 left-handed) all had normal or corrected-to-normal vision and were naïve to the experimental hypotheses.

2.1.2. Stimuli and procedure

Stimuli were presented on a 24 inch BenQ monitor (60 Hz; 1920×1080 screen resolution) at a viewing distance of approximately 90 cm. Stimulus presentation was controlled by E-Prime 2.0 (Psychology Software Tools, Inc.). Stimuli were presented on a grey background, with a black fixation dot ($0.06^\circ \times 0.06^\circ$ of visual angle) appearing constantly throughout a block. On each trial (see Fig. 1), a probe display (50 ms duration) was followed after a 100 ms interstimulus interval by a target display (50 ms duration). These short durations were chosen to remove any incentive for eye-movements towards target-matching probes or targets. Both probe and target displays included a set of coloured Gabor patches ($0.88^\circ \times 0.88^\circ$) that were created using an online generator developed with the OpenSesame software (Mathôt, Schreij, & Theeuwes, 2012) as Gaussian-enveloped sinusoidal gratings ($SD = 12$ pxls; frequency: 10 cycles per degrees). Individual Gabor patches could have one of four possible grating orientations (0° , 45° , 90° , or 135° , with 0° and 90° corresponding to vertical and horizontal lines, respectively), and one of four colours: yellow (CIE colour coordinates: 0.405/.470), green (.296/.604), cyan (.227/.324), or blue (.169/.152). All colours were equiluminant (14 cd/m^2). Probe displays contained a pair of Gabor patches presented to the left and right of fixation at an eccentricity of 0.95° . One of these matched either the colour, the grating orientation, or both the colour and orientation (in conjunction search blocks) of the current target object, whereas the other Gabor patch did not have any target-defining feature. Target displays contained four Gabor patches on the vertical midline (two above and two below fixation; see Fig. 1), covering a vertical distance of 5.41° . The distance between the outer edges of two adjacent patches was 0.64° .

Participants' task was to report the presence or absence of a pre-defined target among the four vertical target display patches, while ignoring the preceding horizontal probe displays. There were three task conditions. In the *conjunction search task*, targets were defined by a specific combination of colour and orientation (e.g., blue patch with horizontal gratings). A different colour/orientation conjunction was selected for each participant, with the provision that each of the four colours and grating orientations served as target feature for three participants. On target-present trials, target patches were accompanied by one colour-matching and one orientation-matching patch as well as one Gabor patch with non-matching orientation and colour. Target-absent search displays contained two colour-matching and two orientation-matching Gabor patches. Target-present and target-absent displays were equally likely to be preceded by probe displays that contained a fully target-matching (i.e., colour- and orientation-matching) Gabor patch, a colour-matching patch, or an orientation-matching patch. These target-matching patches appeared equally likely on the left or right side. In the *colour and orientation search tasks*, targets were defined by a particular colour or orientation, and the other feature dimension was irrelevant. On target-present trials, the target patch was accompanied by three non-matching Gabor patches. On target-absent trials, four non-matching patches were presented. Probe displays in the colour and orientation tasks always contained one target-matching Gabor patch, which appeared with equal probability on the left or right side.

For each participant, the same colour and orientation that defined targets in the conjunction search task were also task-relevant in the colour and orientation search tasks. In all three tasks, there were 50% target-present and 50% target-absent trials. Participants had to press the '1' or '2' keys on the numeric keypad with their right index and middle fingers for target-present or target-absent responses. The interval between the offset of target displays and the onset of the probe display on the next trial was 2350 ms. Experiment 1 included nine consecutive conjunction search blocks, three colour search blocks, and three orientation search blocks (15 blocks in total). The order in which these three task conditions were delivered was counterbalanced across participants. Twelve practice trials were run prior to the first experimental block for each task condition. Each experimental block contained 48 trials. Prior to the start of each experimental block, participants were shown an image of their assigned target feature or feature conjunction on the screen.

2.1.3. 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, with no other offline filters applied. Channels were referenced online to a left-earlobe electrode, and re-referenced offline to an average of both earlobes. Trials with eye-movements (exceeding $\pm 30 \mu\text{V}$ in the HEOG channels), eye blinks (exceeding $\pm 60 \mu\text{V}$ at Fpz) and movement-related artifacts (exceeding $\pm 80 \mu\text{V}$ at all other channels) were rejected. Average data loss of the final sample of 12 participants was 5% ($SD = 3$). The remaining trials were segmented into 600 ms epochs (from 100 ms before to 500 ms after probe display onset). Averaged ERP waveforms were computed for the different types of probe displays (fully-matching, colour-matching, orientation-matching probes in the conjunction search task; colour-matching probes in the colour search task; orientation-matching probes in the orientation search task), separately for probes with target-matching patches in the left or right visual field. N2pc mean amplitudes were quantified based on ERP mean amplitudes obtained at lateral posterior electrode sites PO7 and PO8. Because the N2pc to fully-matching and colour-matching probes emerged earlier than the N2pc to orientation-matching probes (see Results), different post-stimulus latency windows were used to measure N2pc amplitudes for these probes (200–300 ms and 260–360 ms, respectively). Onset latencies of N2pc components to the three different

Table 1
Reaction time (upper row) and error rate (lower row) data in response to target displays in Experiment 1, as a function of search task and target presence (standard deviation in parentheses).

	Conjunction Search		Colour Search		Orientation Search	
	Present	Absent	Present	Absent	Present	Absent
Reaction Time	690 (85)	748 (81)	571 (80)	578 (86)	755 (83)	921 (115)
Error Rate	13 (12)	4 (7)	3 (6)	5 (9)	16 (14)	3 (5)

probe types were determined by assessing grand averaged difference waveforms (contralateral minus ipsilateral ERPs) using a jackknife-based analysis method (Miller, Patterson & Ulrich, 1998). Twelve 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 $-0.5 \mu\text{V}$. These latencies were then compared between probe display types using paired *t*-tests with *t*-values corrected according to the formula described by Miller et al. (1998).

3. Results and discussion

3.1. Behavioural performance

Table 1 shows reaction times (RTs) and error rates for target-present and target-absent trials in the three task conditions. An initial 3×2 repeated-measures Analysis of Variance (ANOVA) conducted on RT data with the factors Search Task (Conjunction, Colour, Orientation) and Target Presence (Present, Absent) showed a main effect of Search Task ($F(2,22) = 79.10, p < 0.001, \eta_p^2 = 0.88$). RTs were fastest for the

colour search task ($M = 574 \text{ ms}$), intermediate during conjunction search ($M = 719 \text{ ms}$), and slowest during orientation search ($M = 838 \text{ ms}$), and differed significantly between all three task conditions (t 's $> 6.06, p$'s < 0.001); There was also a main effect of Target Presence ($F(1,11) = 26.67, p < 0.001, \eta_p^2 = 0.71$), indicating faster RTs on target-present trials ($M = 672 \text{ vs. } 749 \text{ ms}$). A significant Search Task \times Target Presence interaction ($F(2,22) = 19.06, p < 0.001, \eta_p^2 = 0.63$) was due to the fact that target-present RTs were faster than target-absent RTs in the conjunction task ($M = 690 \text{ vs. } 748 \text{ ms}; t(11) = 3.62, p < 0.005$) and the orientation task ($M = 755 \text{ vs. } 921 \text{ ms}; t(11) = 5.69, p = 0.001$), but not in the colour task ($M = 571 \text{ vs. } 578 \text{ ms}; t < 1$).

To assess any differential effects of the three types of probes on RTs in the conjunction search task, an additional analysis was conducted on these data with the factors Probe Type (Fully-matching, Colour-matching, Orientation-matching) and Target Presence (Present, Absent). There was no main effect of Probe Type ($F < 1$) but a significant interaction between Probe Type and Target Presence ($F(2,22) = 4.51, p < 0.03, \eta_p^2 = 0.29$). While RTs on target-absent trials were not affected by Probe Type ($F(2,22) = 1.28, p > 0.25$), there was a significant Probe Type effect for target-present trials ($F(2,22) = 5.28, p < 0.02, \eta_p^2 = 0.32$). Target-present responses were faster for trials with fully-matching probes (681 ms) than for trials with colour- and orientation-matching probes (689 ms and 699 ms, respectively), and the RT difference between trials with fully-matching and orientation-matching probes was significant ($t(11) = 3.08, p = 0.01$).

For error rates, there was no main effect of Search Task ($F(2,22) = 2.34, p > 0.10$), but a significant effect of Target Presence ($F(1,11) = 11.21, p < 0.01, \eta_p^2 = 0.51$), with more misses on target-present trials than false alarms on target-absent trials ($M = 11 \text{ vs. } 4\%$). There was also a significant Search Task \times Target Presence interaction ($F(2,22) = 15.39, p < 0.001, \eta_p^2 = 0.58$). Misses were more frequent

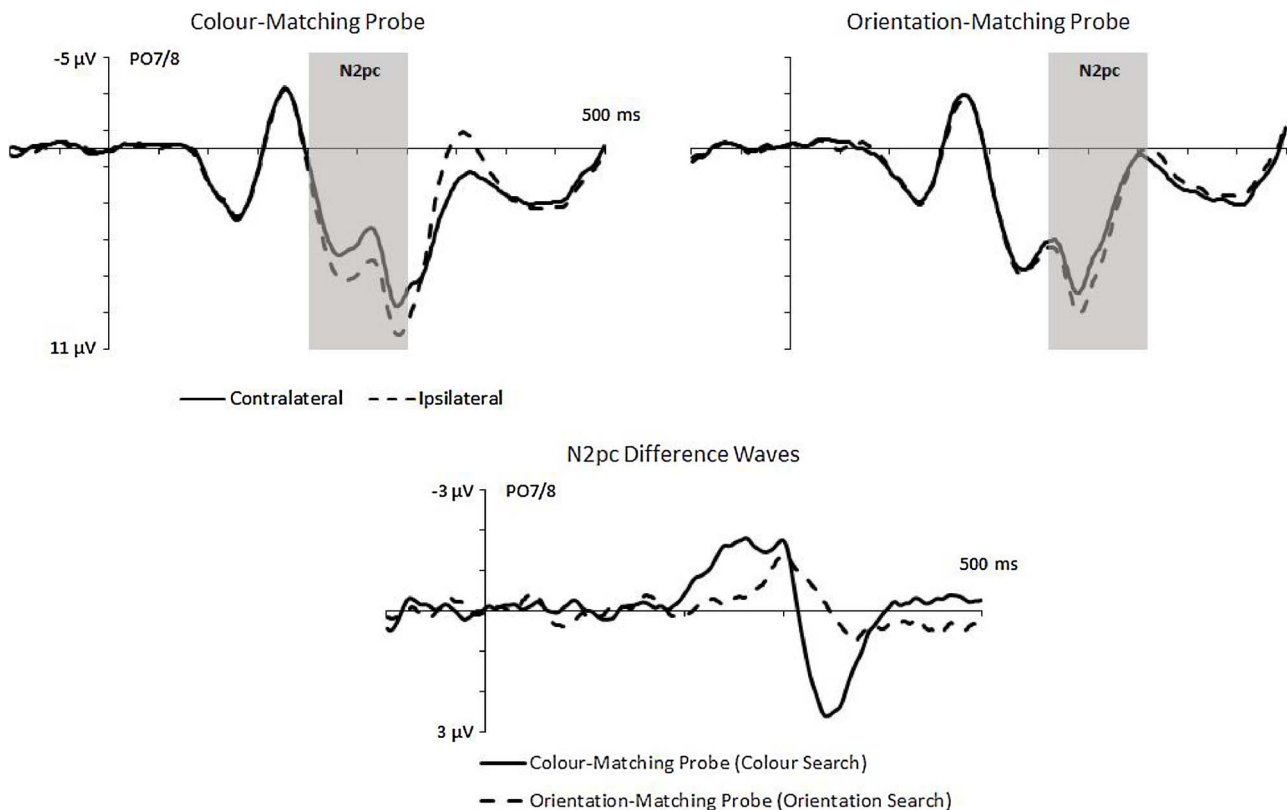


Fig. 2. (Upper panel) Grand average ERPs obtained in Experiment 1 in response to probe displays containing a colour-matching item (in the colour search task) or an orientation-matching item (in the orientation search task) at lateral posterior electrode sites PO7/PO8. ERPs are shown for the 500 ms interval following probe display onset, relative to a 100 ms baseline. (Lower panel) N2pc difference waveforms obtained for colour-matching and orientation matching probes, computed by subtracting ipsilateral from contralateral ERPs.

than false alarms in the conjunction task ($M = 13$ vs. 4%; $t(11) = 3.10$, $p = 0.01$) and the orientation task ($M = 16$ vs. 3%; $t(11) = 4.30$, $p = 0.001$) but not in the colour task ($M = 3$ vs. 5%; $t(11) = 1.56$, $p > 0.10$). There were no reliable effects of Probe Type on error rates in the conjunction search task.

3.2. N2pc components to probe displays

3.2.1. Colour and orientation search

Fig. 2 shows ERPs at electrodes contralateral and ipsilateral to target-matching Gabor patches in the probe displays for the colour and orientation search tasks (top panels), together with the corresponding contralateral/ipsilateral N2pc difference waveforms (bottom panel). Both types of target-matching probes elicited N2pc components, but the N2pc to colour-matching probes emerged earlier than the N2pc to orientation-matching probes. This was confirmed by a jackknife-based N2pc onset analysis with an absolute onset criterion of $-0.5 \mu\text{V}$. The N2pc onset for colour-matching probes ($M = 202$ ms) was significantly earlier than for orientation-matching probes ($M = 268$ ms; $t_c(11) = 3.50$, $p < 0.01$). Because of this clear N2pc latency difference between the two probe types, N2pc mean amplitudes were quantified within a 200–300 ms post-stimulus time window for colour-matching probes, and within a 260–360 ms time window for orientation-matching probes. A direct comparison of contralateral and ipsilateral mean amplitudes within these time windows showed that colour-matching and orientation-matching probes both elicited reliable N2pc components (M diff = -1.37 and $-0.65 \mu\text{V}$; t 's > 3.24 , p 's < 0.01). N2pc amplitudes (i.e., the difference between contralateral and ipsilateral ERPs) tended to be larger for colour-matching probes, and this difference approached significance ($t(11) = 2.16$, $p = 0.053$).

3.2.2. Conjunction search

Fig. 3 shows the ERPs elicited at electrodes contralateral and ipsilateral to the target-matching Gabor patch in probe displays, separately for fully-matching, colour-matching and orientation-matching displays (top panels), together with the corresponding contralateral/ipsilateral N2pc difference waveforms (bottom panel). All three types of probe display appeared to trigger N2pc components, which were largest for fully-matching probes, and delayed for orientation-matching probes. This N2pc onset delay was again confirmed by a jackknife-based latency N2pc analysis with an absolute onset criterion of $-0.5 \mu\text{V}$, which showed a main effect of Probe Type ($F_c(2,22) = 8.23$, $p < 0.005$). Two

planned follow-up analyses showed that the N2pc emerged significantly later for orientation-matching probes ($M = 276$ ms) relative to fully-matching and colour-matching probes ($M = 208$ vs. 210 ms; both t_c 's > 3.56 , p 's < 0.005). Because of the N2pc latency delay for orientation-matching probes, the post-stimulus analysis window was again 260–360 ms for these probes, and 200–300 ms for fully-matching and colour-matching probes. A 3×2 repeated-measures ANOVA with the factors Probe Type (Fully-matching, Colour-matching, Orientation-matching) and Laterality (Ipsilateral, Contralateral) showed a significant main effect of Laterality ($F(1,11) = 43.31$, $p < 0.001$, $\eta_p^2 = 0.80$), confirming that reliable N2pc components were indeed elicited by probe displays in the conjunction search task. A Probe Type \times Laterality interaction ($F(2,22) = 14.89$, $p < 0.001$, $\eta_p^2 = 0.58$) was due to the fact that the N2pc to fully-matching probes was larger than the N2pc to both colour-matching and orientation-matching probes (t 'sn > 3.79 , p 's < 0.005), which did not differ reliably ($t(11) = 1.48$, $p > 0.15$). Comparisons of contralateral and ipsilateral ERPs confirmed that significant N2pc components were present not only for fully-matching probes (M diff = $-1.65 \mu\text{V}$; $t(11) = 8.76$, $p < 0.001$), but also for colour-matching and orientation-matching probes (M diff = -0.84 and $-0.48 \mu\text{V}$; t 's > 2.57 , p 's < 0.03).

4. Experiment 2

In Experiment 1, reliable N2pc components were triggered by target-matching probe stimuli not only in the two feature-based tasks, but also in the conjunction search task. This suggests that feature-based attention operates in a spatially global fashion, allowing target-matching objects at irrelevant locations to attract attention, even when the search task requires a narrow focus of attention. However, one could argue that the attentional focus may still have been relatively wide in Experiment 1, thus preventing the effective spatial filtering of lateral probe stimuli. Target objects appeared with equal probability at one of four locations on the vertical midline in this experiment, and it may generally be difficult to attend to this set of possible target locations above and below fixation without also allocating attention to some degree to objects at nominally irrelevant locations to the left and right of fixation. Experiment 2 was conducted to investigate this possibility. Targets were defined by a conjunction of colour and orientation, and probe display types were the same as in the conjunction search task of Experiment 1. The critical difference was that target location was known precisely in Experiment 2, because there was now

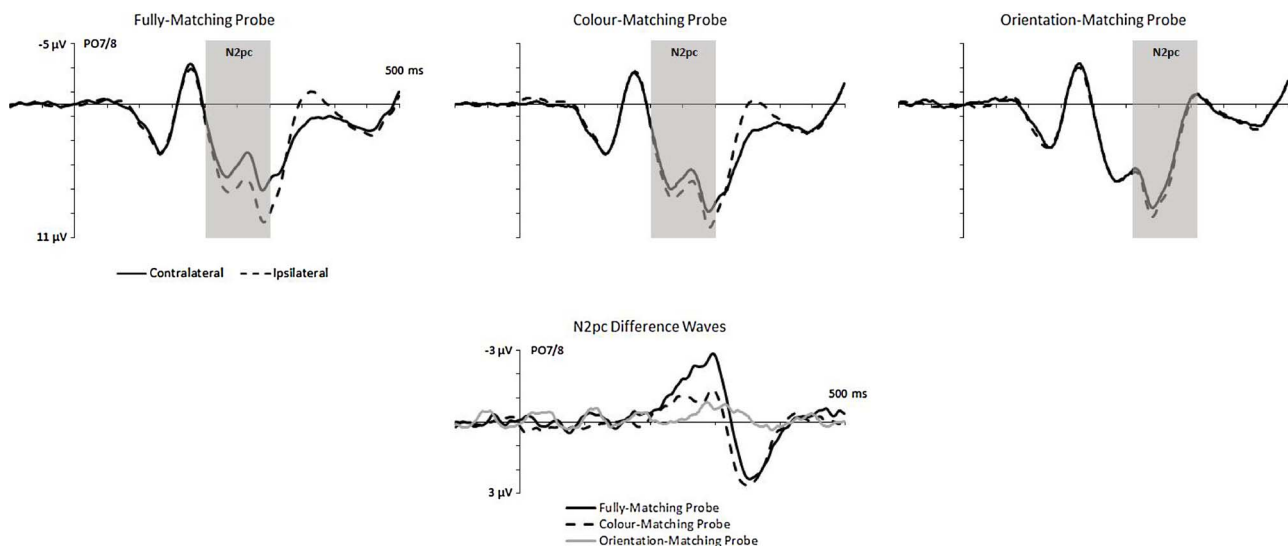


Fig. 3. (Upper panel) Grand average ERPs obtained in Experiment 1 in response to probe displays in the conjunction search task, shown separately for fully-matching probes, colour-matching probes, and orientation-matching probes. ERPs measured at electrodes PO7/8 are shown for the 500 ms interval following probe display onset, relative to a 100 ms baseline. (Lower panel) N2pc difference waveforms obtained for fully-matching, colour-matching, and orientation matching probes, computed by subtracting ipsilateral from contralateral ERPs.

only one task-relevant Gabor patch on each trial that always appeared at fixation. On target-present trials, this patch had both target-defining features. On target-absent trials, it matched either the target colour or orientation. Thus, the task used in Experiment 2 was no longer a conjunction search task (which requires that targets and nontargets appear together in the same display), but a target/nontarget discrimination task that had to be based on the combination of colour and orientation. However, target detection in this task still required the integration of features across dimensions and thus presumably focal attention. Because there was only a single task-relevant location, Experiment 2 provides a strong test of the hypothesis that the feature-guided allocation of attention to objects at irrelevant locations cannot be prevented by spatial filtering mechanisms. If this was correct, the pattern of N2pc results should be the same as in the conjunction search task of Experiment 1, with reliable N2pc components triggered by partially and fully-matching probe stimuli.

5. Method

5.1. Participants

Thirteen participants took part in Experiment 2. One participant was excluded due to excessive artifact rejection (> 50%). Of the remaining 12 participants (M age = 31 years; $SD = 6$, 5 male, 2 left-handed), all had normal or corrected-to-normal vision and were naïve to the experimental hypotheses.

5.2. Stimuli and procedure

Procedures were identical to the conjunction search task of Experiment 1, with the following exceptions. Task-relevant displays no longer contained four vertically oriented Gabor patches, but only a single patch that was always presented at fixation. Targets were again defined by a specific combination of colour and orientation, and were present on 50% of all trials. On target-absent trials, the Gabor patch at fixation matched either the target colour or its orientation. The inter-trial interval between the offset of a task-relevant display and the onset of the next probe display was 1850 ms. Each task-relevant central Gabor patch was preceded by one of three possible bilateral probe displays that were identical to the conjunction search task of Experiment 1 (fully-matching, colour-matching, or orientation-matching probes). Participants completed 10 experimental blocks of 36 trials.

5.3. EEG recording and data analysis

Recording and analysis methods were analogous to Experiment 1. N2pc amplitudes were quantified based on ERP mean amplitudes obtained between 200 and 300 ms (for fully and colour-matching probes) and 300–400 ms (for orientation-matching probes). Artifact rejection resulted in an average data loss for the final sample of 12 participants of 6% ($SD = 5$).

6. Results and discussion

6.1. Behavioural results

A 3×2 repeated-measures ANOVA conducted on RT data with the factors Probe Type (Fully-matching, Colour-matching, Orientation-matching) and Target Presence (Present, Absent) showed a significant main effect of Probe Type ($F(2,22) = 10.34$, $p = 0.001$, $\eta_p^2 = 0.49$), with RTs significantly faster on trials with fully-matching probes ($M = 488$ ms) relative to both colour and orientation-matching probe trials ($M = 497$ and 503 ms respectively; t 's > 2.76, p 's < 0.02). RTs did not differ between trials with colour-matching and orientation-matching probes ($t(11) = 1.58$, $p > 0.10$). There was no significant main effect of Target Presence ($F(1,11) = 1.30$, $p > 0.25$), but a

significant interaction between Probe Type and Target Presence ($F(2,22) = 19.09$, $p < 0.001$, $\eta_p^2 = 0.63$). Similar to Experiment 1, there was an effect of Probe Type for target-present RTs ($F(2,22) = 24.04$, $p < 0.001$, $\eta_p^2 = 0.69$), with faster RTs on trials with fully-matching probes (468 ms) than trials with colour-matching probes (491 ms), and slowest RTs on trials with orientation-matching probes (506 ms; all t 's > 2.54, p 's < 0.03). In contrast, target-absent RTs were not affected by probe type ($F(2,22) = 1.65$, $p > 0.20$; 508 ms, 504 ms, and 500 ms, for trials with fully-matching, colour-matching, and orientation-matching probes).

For error rates, there was a main effect of Probe Type ($F(2,22) = 3.74$, $p < 0.05$, $\eta_p^2 = 0.25$), with errors more frequent on trials with orientation-matching probes ($M = 4\%$) relative to trials with fully-matching and colour-matching probes ($M = 2\%$ and 3% ; $t(11) = 2.36$ and 2.91 , both $p < 0.05$). There was a trend for a main effect of Target Presence ($F(1,11) = 3.52$, $p = 0.088$, $\eta_p^2 = 0.24$), and a significant Probe Type \times Target Presence interaction ($F(2,22) = 4.95$, $p < 0.02$, $\eta_p^2 = 0.31$). Misses on target-present trials were more frequent when targets were preceded by an orientation-matching probe ($M = 5\%$) than on trials with a fully-matching or colour-matching probe ($M = 2\%$ and 3% ; main effect of Probe Type: $F(2,22) = 5.57$, $p < 0.02$, $\eta_p^2 = 0.34$). In contrast, the frequency of false alarms on target-absent trials was not reliably affected by Probe Type ($F(2,22) = 1.69$, $p > 0.20$; $M = 3\%$, 3% , and 2% for trials with fully-matching, colour-matching, and orientation-matching probes).

6.2. N2pc components to probe displays

Fig. 4 shows contralateral and ipsilateral ERPs in response to fully-matching, colour-matching and orientation-matching Gabor patches in the probe displays (top panels), and the corresponding contralateral/ipsilateral N2pc difference waveforms (bottom panel). Similar to Experiment 1, all three types of probes elicited N2pc components. The N2pc to orientation-matching probes was again delayed relative to the N2pc to fully-matching and colour-matching probes, as confirmed by a jackknife-based N2pc latency analysis with an absolute onset criterion of $-0.5 \mu\text{V}$, which obtained a significant main effect of Probe Type ($F_c(2,22) = 85.6$, $p < 0.001$). Two planned comparisons of N2pc onset latencies to orientation-matching probes ($M = 314$ ms) versus fully-matching and colour-matching probes ($M = 227$ ms and 207 ms) confirmed that this delay was reliable (both t_c 's > 8.45, p 's < 0.001).

Given the onset delay of the N2pc to orientation-matching probes, analyses of N2pc mean amplitudes were based on ERP mean amplitudes obtained within a 300–400 ms post-stimulus window for these probes, and on a 200–300 ms window for fully-matching and colour-matching probes. A significant effect of Laterality ($F(1,11) = 15.37$, $p < 0.005$, $\eta_p^2 = 0.58$) confirmed the presence of significant N2pc components in Experiment 2. These components were reliably present for all three probe display types (fully-matching: M diff = $-1.02 \mu\text{V}$; $t(11) = 3.26$, $p < 0.01$; colour-matching: M diff = $-0.90 \mu\text{V}$; $t(11) = 3.35$, $p < 0.01$; orientation-matching: M diff = $-0.47 \mu\text{V}$; $t(11) = 2.51$, $p < 0.03$). Even though N2pc amplitudes were numerically largest for fully-matching and smallest for orientation-matching probes, the Probe Type \times Laterality interaction was not significant ($F(2,22) = 2.08$, $p = 0.15$).

7. Discussion

The aim of the current experiments was to test whether or not attentional selection processes guided by target templates operate in a spatially global fashion, even at locations that are known to be task-irrelevant. Previous behavioural and electrophysiological studies investigating this question (Folk et al., 2002; Leblanc et al., 2008; Leonard et al., 2015) have all used a paradigm where targets defined by a unique colour appeared within a central RSVP stream and were preceded by distractors at task-irrelevant locations on the left or right side.

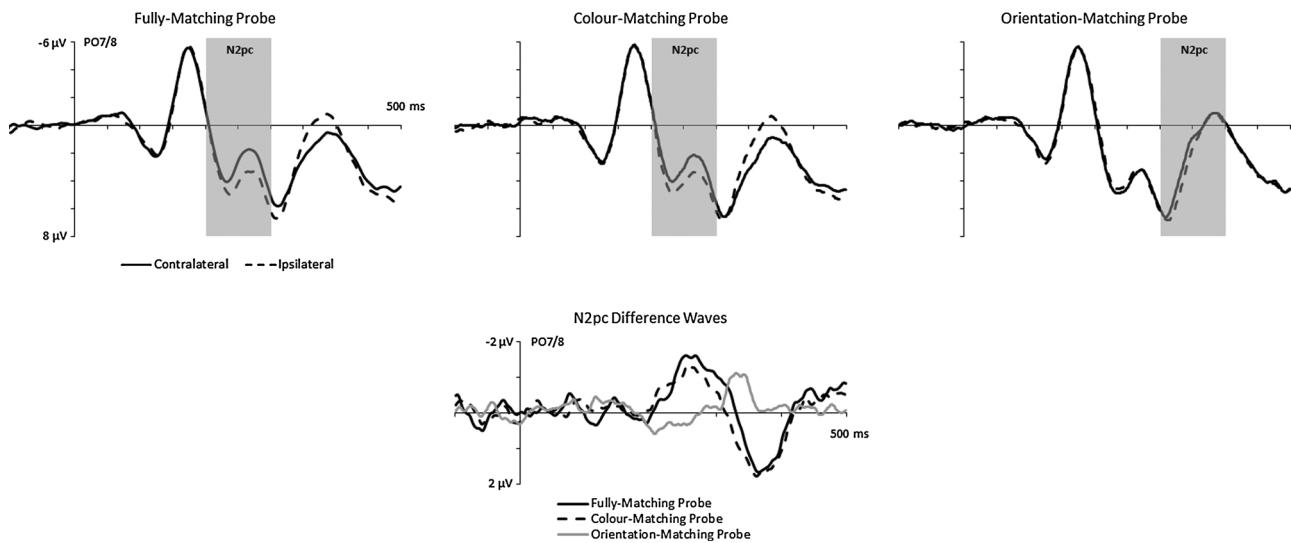


Fig. 4. (Upper panel) Grand average ERPs obtained in Experiment 2 in response to fully-matching, colour-matching, and orientation-matching probes, measured at electrodes PO7/8 during the 500 ms interval following probe display onset, relative to a 100 ms baseline. (Lower panel) N2pc difference waveforms obtained for fully-matching, colour-matching, and orientation matching probes, computed by subtracting ipsilateral from contralateral ERPs.

When these distractors matched the target colour, they impaired target detection and triggered N2pc components, demonstrating that feature-guided attentional capture cannot be prevented at irrelevant locations. Because these findings may be specific to the attentional selection demands associated with RSVP tasks, or to situations where targets and nontargets can be discriminated on the basis of a unique feature, we investigated the generality of this conclusion for visual search tasks where targets were defined either by a specific feature or by a feature conjunction. Experiment 1 demonstrated that target-matching probes at task-irrelevant locations remain able to capture attention, as reflected by significant N2pc components, when participants search for targets within a single subsequent search display. This shows that such capture effects are not specific to tasks where infrequent targets have to be detected in RSVP streams, but are also elicited during more typical visual search tasks. The N2pc to colour-matching probes emerged substantially earlier than the N2pc to orientation-matching probes (Figs. 2 and 3), indicating that colour signals were more effective in rapidly activating feature-based attention than orientation signals.

Critically, reliable N2pc components to target-matching probes were not only found when targets were defined by a unique feature (colour or orientation), but also when targets were defined by a colour/orientation conjunction. This rules out the possibility that feature-based attentional capture effects at irrelevant locations were found in previous studies because target/nontarget discriminations were based on a single feature and thus did not require focal attention. In Experiment 1, RTs were much slower in the conjunction search than during colour or orientation search, in line with the hypothesis that the detection of targets defined by feature conjunctions is assumed to require a narrow focus of attention and serial attentional shifts between individual objects (Treisman & Gelade, 1980; Treisman, 1988). In spite of these increased demands on attentional selectivity in the conjunction search task, probes at task-irrelevant locations that matched one or both target features were still able to attract attention. This shows that even in tasks that require the focal attentional processing of target objects at known task-relevant locations, top-down filtering processes cannot prevent the activation of spatially global feature-based attention. Experiment 2 demonstrated that this remains the case when conjunctively defined targets or partially-matching nontargets are always presented at a single known location (at fixation). This rules out the possibility that the attentional capture effects observed during conjunction search in Experiment 1 were due to the fact that targets appeared unpredictably at one of four locations on the vertical midline, and shows that target-

matching objects at irrelevant peripheral locations will attract attention even when spatial attention is narrowly focused at fixation.

In previous behavioural studies of feature-based attentional capture at ignored locations (Folk et al., 2002; Leonard et al., 2015), performance costs for targets preceded by peripheral colour-matching distractors were interpreted as evidence that these distractors attracted attention to their location, which interfered with the subsequent detection of target events in the central RSVP stream. As all probe displays contained a target-matching feature in the present study, it was not possible to measure analogous interference effects on performance. It is likely that such effects will be more pronounced in RSVP tasks, where the detection of targets requires attention to be focused at a particular location at a specific moment in time, compared to single-frame search tasks where the time demands on attentional selectivity are less severe. In fact, target-present responses in the conjunction search tasks of Experiments 1 and 2 were faster on trials with fully-matching as compared to partially-matching probes, in spite of the fact that fully-matching probes tended to attract attention more strongly, as reflected by larger N2pc components. These RT benefits are likely to reflect the priming of target-present responses by fully-matching probes. If this is correct, it shows that the conjunctively defined identity of target-matching probe objects was detected, which provides additional evidence that these objects were attentionally processed in spite of being presented at task-irrelevant locations.

While the current results show that the demands of a central attentional selection task do not affect the ability of peripheral target-matching features to attract attention, it is possible that further variations of this task design might result in a stronger impact of top-down filtering on attentional capture. Although attending to target-matching probe stimuli had the potential to interfere with the focal-attentional processing of candidate target stimuli, in particular in the conjunction search tasks, participants may still have directed attention to these probes on some trials because their onset predicted the onset of the subsequent target displays, or because they may have been useful to refresh the attentional template for the current target features(s). This could be tested in future experiments by varying the interval between probes and targets, or by presenting probe stimuli only in a subset of all trials.

The observation that target-matching probes elicited reliable N2pc components in the present study shows that feature-guided attentional capture cannot be prevented by top-down spatial filtering mechanisms. However, these filtering mechanisms may still have an effect at

processing stages that follow the initial rapid allocation of attention that is reflected by the onset of the N2pc. For example, attention may be rapidly withdrawn from target-matching objects at locations that are known to be task-irrelevant, but not from objects at locations that may contain a target (see Theeuwes, Atchley, & Kramer, 2000, for an analogous argument regarding the time course of salience-driven attentional capture by task-irrelevant singletons). If this was the case, N2pc components to objects with target-matching features should be triggered at the same time regardless of whether these objects appear at relevant or irrelevant locations, but these components may be transient for irrelevant-location objects and more sustained at relevant locations. This prediction will need to be investigated in future experiments.

Overall, the current study has provided new evidence for the spatially global nature of template-guided attentional selection processes by demonstrating that objects with target-matching features remain able to attract attention when they appear at locations that have to be ignored, even in tasks that require a narrow focus of spatial attention elsewhere. There are two basic forms of top-down attentional control mechanisms that usually operate together to facilitate the adaptive allocation of attention to currently relevant objects and events (e.g., Folk et al., 2002). Attentional guidance produces spatially global biases for objects with task-relevant features, whereas spatial filtering acts to exclude objects at irrelevant locations from attentional processing. The current results show that when these two mechanisms are in conflict, rapid template-based attentional guidance processes that are triggered within 200–300 ms after stimulus onset cannot be overridden by spatial filtering.

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