

Target objects defined by a conjunction of colour and shape can be selected independently and in parallel

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Published online: 28 August 2017
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Abstract It is generally assumed that during search for targets defined by a feature conjunction, attention is allocated sequentially to individual objects. We tested this hypothesis by tracking the time course of attentional processing biases with the N2pc component in tasks where observers searched for two targets defined by a colour/shape conjunction. In Experiment 1, two displays presented in rapid succession (100 ms or 10 ms SOA) each contained a target and a colour-matching or shape-matching distractor on opposite sides. Target objects in both displays elicited N2pc components of similar size that overlapped in time when the SOA was 10 ms, suggesting that attention was allocated in parallel to both targets. Analogous results were found in Experiment 2, where targets and partially matching distractors were both accompanied by an object without target-matching features. Colour-matching and shape-matching distractors also elicited N2pc components, and the target N2pc was initially identical to the sum of the two distractor N2pcs, suggesting that the initial phase of attentional object selection was guided independently by feature templates for target colour and shape. Beyond 230 ms after display onset, the target N2pc became superadditive, indicating that attentional selection processes now started to be sensitive to the presence of feature conjunctions. Results show that independent attentional selection processes can be activated in parallel by two target objects in situations where these objects are defined by a feature conjunction.

Keywords Attention · Cognitive and attentional control · Electrophysiology

The successful detection of a looked-for target object among irrelevant distractors in a visual scene requires top-down attentional control. When some or all features of such a target are known in advance, these features are represented internally as attentional templates (Duncan & Humphreys, 1989; Desimone & Duncan, 1995). Activating such templates during the preparation for visual search will prioritize the visual processing of template-matching features and can guide selective attention towards the location of candidate target objects in the visual field (e.g., Olivers, Peters, Houtkamp, & Roelfsema, 2011; Wolfe, 2007). The time course and nature of such template-guided attentional selection processes remains a topic of lively debate. One important controversial issue concerns the question of whether these processes operate in a strictly sequential fashion, with serial shifts of attention between successively selected objects, or whether attention can be allocated to multiple objects simultaneously. Leading models of visual search (e.g., Treisman & Gelade, 1980; Wolfe, 1994, 2007) postulate that attentional object selection is a serial process, particularly in situations when target objects are defined by a combination of features, and some of the distractor objects in the search display also possess target-matching features (conjunction search). In contrast, other models of attentional control (e.g., Desimone & Duncan, 1995) and accounts of the role of attention in multiple object tracking tasks (e.g., Cavanagh & Alvarez, 2005; see also Niebergall, Khayat, Treue, & Martinez-Trujillo, 2011) assume that attention can be allocated in parallel to several objects in the visual field.

This debate about the parallel versus serial nature of attentional selection mechanisms in visual search is closely linked

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to the question of how visual processing biases in favour of possible target objects emerge in real time and are difficult to resolve based on behavioural measures alone. Because event-related brain potential (ERP) markers of attentional selectivity track the emergence of such processing biases on a millisecond-by-millisecond basis, they can provide more comprehensive insights into the temporal and spatial properties of attentional selection processes. Many electrophysiological studies of visual attention and visual search have measured the N2pc component, which is commonly interpreted as marking the allocation of attention to candidate target objects that appear among distractors in visual search displays (e.g., Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999). The N2pc is an enhanced negativity that is elicited at posterior electrodes contralateral to the visual field of such objects, typically emerges around 180–200 ms after stimulus onset, and is generated in extrastriate areas of the ventral visual processing stream (Hopf et al., 2000). At the physiological level, the N2pc reflects the presence of a spatially selective attentional bias of visual activity in retinotopic visual regions that is triggered by task-relevant features at specific locations in a search display. At the cognitive level, the emergence of such processing biases can be described as reflecting the attentional selection of specific target features or objects (see Eimer, 2014, 2015, for further details).

Most N2pc studies have used search displays that include just a single visual object with target-defining features. To investigate the serial versus parallel nature of attentional selection processes, search tasks are required where multiple possible target objects are present in the same display. Because the N2pc is computed by comparing contralateral and ipsilateral ERP waveforms to targets in the left versus right visual field, this component cannot track one particular selection process in displays where several candidate target objects appear simultaneously in both hemifields, as these objects will produce N2pcs of opposite polarity that will cancel each other out. This methodological problem can be overcome by using the fact that nonlateralised target objects on the vertical midline do not elicit N2pc components. In search displays where one candidate target object appears above or below fixation and another candidate target on the left or right side, any N2pc response will exclusively reflect the allocation of attention to the lateral target, independently of any additional selection processes that are triggered by the vertical target (see Eimer, Kiss, & Nicholas, 2011; Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, & Theeuwes, 2006; Woodman & Luck, 1999, 2003, for previous N2pc studies that employed this logic).

In a recent series of experiments (Eimer & Grubert, 2014b; Grubert & Eimer, 2015; Jenkins, Grubert, & Eimer, 2016), we used this horizontal/vertical target presentation procedure to investigate the time course of attentional selection processes in tasks where two target objects appeared in two successively

presented displays that were separated by a very short stimulus onset asynchrony (SOA). In one study (Eimer & Grubert, 2014b), participants had to compare the identity of two colour-defined targets that were presented together with a nontarget-colour item on the opposite side, either on the horizontal or vertical midline. The horizontal display either preceded or followed the vertical display, and these two types of trials were randomly intermixed. N2pc components of similar size were elicited by horizontal targets in the first and second display, and the onset difference between these N2pc components closely matched the objective SOA between the two displays (which was varied between 10 ms and 100 ms). With short SOAs, these two N2pc components also overlapped in time. Very similar N2pc results have been observed when both target-colour objects were presented simultaneously in the same display (Grubert & Eimer, 2016) and also when two successively presented targets differed in their colour (Grubert & Eimer, 2015). These observations suggest that colour-guided attentional selection processes can operate in parallel for multiple target objects at different locations, with each selection process following its own independent time course. Such rapid and apparently parallel attentional target selection processes are not confined to tasks where attention is guided by colour, as very similar temporal patterns of N2pc components were also found in a task with shape-defined targets, and even when targets were defined by their alphanumeric category (Jenkins et al., 2016).

These observations suggest that attention can be allocated rapidly and independently to multiple target objects in tasks where these objects can be discriminated from nontargets based on one particular feature. However, in real-world environments, it is often not possible to distinguish a relevant object from irrelevant distracting objects on the basis of a single feature. For example, search for large silver coins among small silver coins and large bronze coins has to be based on two target-defining attributes from different feature dimensions (colour and size). Behavioural studies have demonstrated that this type of conjunction search is typically less efficient than search for targets that are defined by a single feature (e.g., Treisman & Gelade, 1980). According to Feature Integration Theory (e.g., Treisman, 1988), this is because feature search can operate in parallel for multiple objects, whereas conjunction search requires serial shifts of spatial attention between individual objects. Response times (RTs) in conjunction search tasks increase with the number of distractor objects possessing one target-defining feature but remains unaffected by the number of nontarget objects without task-relevant features (Egeth, Virzi, & Garbart, 1984), suggesting that search can be restricted to the subset of objects with target features but that search within this subset is conducted serially. Others (e.g., Wolfe, 1998) have argued that the serial/parallel dichotomy is misleading, and that search efficiency varies continuously between different types of search tasks. According to the

Guided Search model (Wolfe, 1994, 2007), search performance depends on the efficiency with which attentional object selection can be guided towards the location of target objects. Guidance is controlled by a spatiotopic salience map where information about the location of target-defining attributes is combined. Attention is then directed serially to those locations that are most likely to contain a target object.

The goal of the present study was to investigate the speed with which attention can be allocated to two target objects presented in rapid succession under conditions where these targets are defined by a conjunction of features. We employed the same rapid sequential presentation paradigm as in our previous studies of feature-guided attentional selection processes (e.g., Eimer & Grubert, 2014b), except for the fact that targets were now defined by a particular combination of colour and shape. In Experiment 1, targets were always accompanied by a distractor object in the same display that either matched the target colour or the target shape. Two target/distractor displays were presented successively for 50 ms each, and were separated by an SOA of 10 ms or 100 ms (in different blocks). The target/distractor pair was presented on the horizontal midline in one of these displays and on the vertical midline in the other display (see Fig. 1). The order in which these two displays were presented (horizontal first or second: H1 or H2 targets) varied unpredictably across trials. Participants had to attend to the two target objects defined by a specific colour/shape conjunction (e.g., blue circles), and to report whether the gaps in their contours were located on the same side or on opposite sides. To assess the time course with which attention was allocated to the two conjunctively defined target objects, we measured N2pc components, separately for H1 and H2 targets and for the two SOA conditions.

Because one target was accompanied by a colour-matching distractor and the other by a shape-matching distractor on each trial, target selection could not be based on a single search template for a particular feature. According to Feature Integration Theory (Treisman & Gelade, 1980), the identification of these target objects will have to be based on the integration of signals across the colour and shape dimensions, and this requires focal attention that can only be allocated in a serial fashion to one object at a time. In the Guided Search model, different features can guide attention independently and in parallel, but the resulting feature-guided attentional selection of objects is assumed to operate in a serial fashion (Wolfe, 2007). Both models predict that the selection of the target object in the second display can only commence after attention is withdrawn from the first target. If N2pc components mark the points in time when attention is allocated to H1 and H2 targets, respectively, their temporal pattern should differ from the pattern observed in our previous studies where these targets were defined by a single feature. It is possible that serial attention shifts can take place within 100 ms. In this case, both H1 and H2 targets should trigger N2pc components of similar size

in blocks where the two displays are separated by 100 ms (SOA 100 condition), and their onset latency difference should match the objective SOA between the two displays. Critically, qualitatively different results should be observed in blocks with a 10-ms SOA between the two displays. In these blocks, the time required to initiate a shift of attention from the first to the second target should be considerably longer than the SOA between these targets. Given that each display was presented for only 50 ms, this might make it difficult to allocate attention to the second target at all while it is still perceptually available. As a result, N2pc components to H2 targets should be delayed, attenuated, or perhaps even entirely absent in the SOA 10 condition of Experiment 1. In addition, there should also be performance costs relative to the SOA 100 condition, where more time is available to complete serial attention shifts.

The alternative possibility is that attention can be allocated independently and in parallel to both target objects even when these targets are defined by a feature conjunction. In this case, temporally overlapping N2pc components of similar size should be elicited by H1 and H2 targets in the SOA 10 condition, as was observed previously with feature-defined targets (e.g., Eimer & Grubert, 2014b). To preview the results, this was indeed what was found in Experiment 1. The feature-based versus object-based nature of these parallel attentional processing biases was investigated in Experiment 2.

Experiment 1

Method

Participants

Fifteen participants were paid to take part in Experiment 1. Three of them were excluded from analysis due to excessive eye-movement activity. The remaining 12 participants were aged between 20 and 41 years ($M = 30.25$, $SD = 6.52$). Eight were female and three were left-handed. All participants had normal or corrected-to-normal vision. This choice of sample size ($n = 12$, after excluding three participants) was based on a power analysis that employed the effect size obtained from a previous N2pc experiment in our lab (Jenkins et al., 2016), in which the same sample size was used to compare N2pc onset latencies across multiple displays and SOA conditions in response to rapidly presented shape-defined target stimuli.¹

¹ To ensure a large enough sample size providing enough power to reliably exclude false rejection of the null hypothesis, power ($1 - \beta$) was calculated using the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007), using the a priori option and the η_p^2 effect size (.72) of the SOA * Display sequence interaction of Experiment 1 in Jenkins et al. (2016; $n = 12$). Power analysis revealed a test power of .872 (with an effect size f determined according to Cohen, 1988, of 1.60) and suggested that a sample size of $n = 4$ was sufficient to achieve the desired effect size of .72.

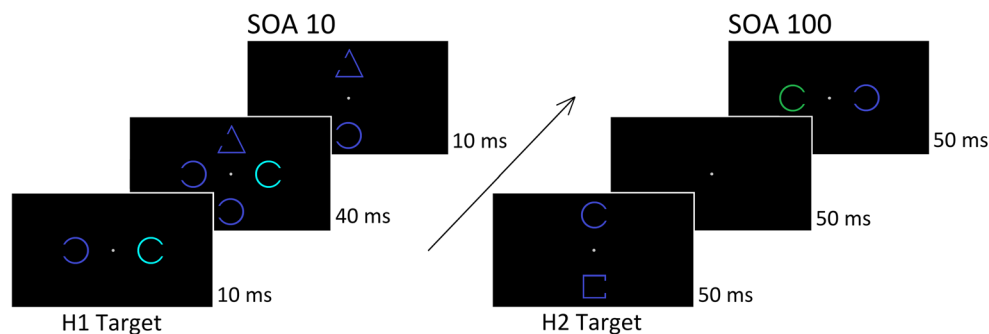


Fig. 1 Schematic illustration of the search displays and the time course of events in the SOA 10 and SOA 100 conditions of Experiment 1. On each trial, two consecutive search displays contained a target defined by a specific colour/shape conjunction (a *blue circle* in the examples shown here) and a colour-matching or shape-matching distractor on opposite

sides. Participants' task was to decide whether the two target objects had a gap on the same or on different sides. Displays with horizontal target/distractor pairs preceded vertical displays (H1 target) or vice versa (H2 target). (Colour figure online)

Stimuli and procedure

Stimuli were presented on a 22-inch Samsung wide SyncMaster 2233 LCD monitor (resolution of 1280×1024 pixels, 100-Hz refresh rate; 16-ms black-to-white-to-black response time, verified using a photodiode). Participants were seated in a dimly lit cabin and viewed the screen from an approximate distance of 100 cm. Stimulus presentation, timing, and response collection were controlled by a LG Pentium PC operating under Windows XP, using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (MathWorks, Inc.). Stimuli were coloured outline shapes (circles, squares, or triangles; 0.2° line width), subtending $1.1^\circ \times 1.1^\circ$ of visual angle. There was a gap in the contour of each object, on the left or right side. The size of this gap was 0.6° , and it was always centred between the top and bottom of each shape (as illustrated in Fig. 1). The possible stimulus colours were blue (CIE colour coordinates: .185/.188), cyan (.212/.347), or green (.262/.572). All colours were equiluminant (9.8 cd/m^2). Stimuli were presented at an eccentricity of 3.0° from central fixation against a black background. A central grey (.321/.352) fixation point ($0.2^\circ \times 0.2^\circ$) remained continuously present for the duration of each experimental block.

On each trial, two successive stimulus displays were each presented for 50 ms. Each stimulus display contained one target object (matching both the target shape and colour) and a distractor on opposite sides. One of the two distractors in each trial matched the target shape but had one of the two nontarget colours (shape-matching distractor). The distractor in the other display on the same trial matched the target colour but had one of the two nontarget shapes (colour-matching distractor). Nontarget colours and shapes were randomly selected on each trial. One target/distractor pair was presented on the horizontal meridian (left and right of fixation), and the other pair appeared on the vertical meridian (above and below fixation). In half of all trials, the horizontal stimulus pair was presented first (horizontal target first: H1 target). In the other

half, the vertical target/distractor display preceded the horizontal display (horizontal target second: H2 target). These two display sequences were randomly intermixed in each block. The position of the two target objects in the two displays (left/right; top/bottom), as well as the order in which the shape-matching and colour-matching distractors appeared, were randomly and independently determined on each trial. There were two blocked SOA conditions. In SOA 10 blocks, the onset of the first display preceded the onset of the second display by 10 ms (i.e., there was a 40-ms overlap between these two displays). In SOA 100 blocks, the onset of the two consecutive displays was separated by 100 ms, and there was a 50-ms blank interval between the offset of the first display and the onset of the second display. The interval between the offset of the second display and the onset of the first display on the next trial was 1,900 ms.

Each participant was assigned a specific target-defining shape/colour conjunction that remained constant throughout the experiment. Each of the three possible shapes (circle, square, and triangle) and colours (blue, green, and cyan) served as target-defining feature for four participants. Target colour and shape were selected independently, with the constraint that each of the nine possible colour-shape conjunctions served as target for at least one of the 12 participants (with three of these conjunctions each serving as target for two participants). Participants were instructed to find the two target objects in the two successively presented displays, and to report whether these objects had gaps on the same side (both left or right) or on different sides (one left, one right) by pressing one of two purpose-built vertically aligned response keys. The response-to-key mapping, as well as the hand-to-key mapping, was counterbalanced across participants. Trials requiring a "same" or "different" response were equiprobable and randomly intermixed in each block.

The experiment contained 12 blocks, with 64 trials per block, and four trials for each combination of display sequence (H1 target, H2 target), position of horizontal target (left, right), position of vertical target (top, bottom), and

sequence of partially matching distractors (shape-matching followed by colour-matching distractor, or vice versa). Each SOA condition was run in six successive blocks, and the order of the SOA conditions was counterbalanced across participants. Each of the two SOA conditions was preceded by one practice block.

EEG recording and data analyses

The continuous EEG was DC-recorded from 27 scalp electrodes at standard positions of the extended 10–20 system, sampled at a rate of 500 Hz, and digitally low-pass filtered at 40 Hz. No other off-line filters were applied. All channels were online referenced to the left earlobe and rereferenced off-line to the average of both earlobes. Trials contaminated with artefacts (eye movements exceeding ± 30 μV in the HEOG channels; eye blinks exceeding ± 60 μV at Fpz; muscular movements exceeding ± 80 μV in all other channels), and trials with incorrect, anticipatory (faster than 200 ms), very slow (slower than 1,500 ms), or missing responses were excluded from EEG analyses. This led to an exclusion of an average of 12.3% and 17.6% of all trials in the SOA 10 and SOA 100 conditions, respectively. For the remaining trials, EEG was segmented into epochs ranging from 100 ms prior to 500 ms after the onset of the first stimulus display, and was baseline corrected relative to the 100 ms interval prior to the onset of the first display. EEG was averaged separately for each of the eight combinations of SOA (10 ms, 100 ms), display sequence, and position of horizontal target.

N2pc components were quantified on the basis of ERP waveforms measured at lateral posterior electrodes PO7 and PO8. N2pc onset latencies were measured based on difference waveforms, computed by subtracting ipsilateral from contralateral ERPs at PO7 and PO8. Onset latencies were determined with a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). Twelve grand-average difference waves were computed for each experimental condition, each excluding one different participant from the original sample. N2pc onset latency was defined as the point in time when each subsample difference wave reached an absolute onset criterion of -1 μV .² Differences in N2pc onset latencies between H1 and H2 targets and between SOA conditions were assessed with repeated-measures ANOVAs and *t* tests, with *F* and *t* values corrected according to the formulas described by Ulrich and Miller (2001) and Miller et al. (1998), respectively. The corrected

statistical values are indicated with F_c and t_c , respectively. All *t* tests were two-tailed and Bonferroni corrected where necessary. To measure effect sizes, Cohen's *d* (Cohen, 1988) was computed for all *t* tests, and partial eta-squared (labelled η_p^2) was computed for all ANOVAs. In order to correct individual group means and standard deviations of jackknifed samples, the N2pc latency group means obtained through the jackknife procedure were fed into repeated-measures ANOVAs, from which the error variance was corrected according to the formula described by Ulrich and Miller (2001). For this reason, effect sizes from N2pc latency analyses are reported as η_p^2 .

N2pc mean amplitudes were computed within 100 ms time intervals. For H1 targets, a 200–300-ms time interval after the onset of the first display was employed for both SOA conditions. For H2 targets, time windows were adjusted relative to the SOA between the first and second display (210–310 ms after the onset of the first display for the SOA 10 condition; 300–400 ms for the SOA 100 condition).

Results

Behavioural performance

Reaction times (RTs) were measured relative to the onset of the second display on each trial. Anticipatory or exceedingly slow RTs (faster than 200 ms or slower than 1,500 ms) were removed from analysis, resulting in the exclusion of less than 1% of all trials. A repeated-measures ANOVA, with the factors SOA (10 vs. 100 ms) and display sequence (H1 vs. H2 targets) was run separately for RTs and for error rates. RTs were faster in the SOA 10 than in the SOA 100 condition (682 ms vs. 727 ms), but this difference was not significant, $F(1,11) = 4.06$, $p = .069$, $\eta_p^2 = .27$. There was also no main effect of display sequence on RTs (705 ms vs. 704 ms for H1 and H2 targets, respectively), nor any interaction between these two factors, both $F(1,11) = .01$, $p = .916$, $\eta_p^2 = .00$. For error rates, a main effect of SOA was observed, $F(1, 11) = 22.21$, $p < .001$, $\eta_p^2 = .67$, with more errors in the SOA 100 condition than in the SOA 10 condition (10.1% vs. 4.4%). There was no effect of display sequence on error rates (7.1% and 7.4% for H1 and H2 targets, respectively) and no interaction between these two factors, both $F(1,11) < 1.11$, $p = .745$, $\eta_p^2 = .01$.

N2pc components

Figure 2 (left and middle panels) shows ERPs at posterior electrodes PO7/8 contralateral and ipsilateral to the side of the horizontal conjunction target for trials where this target appeared in the first display (H1 targets) or in the second display (H2 targets). The right panel of Fig. 2 shows N2pc difference waveforms obtained by subtracting ipsilateral from

² A fixed onset criterion of -1 μV was chosen to avoid distortion of N2pc onset latency estimates by differences in N2pc amplitude between experimental conditions. All N2pc onset latency analyses reported in this article were additionally run with a relative onset criterion of 50% (defined by the point in time when 50% of the N2pc peak amplitude is reached for each subsample difference wave), as described by Miller et al. (1998). The results of these analyses confirmed those obtained with the fixed onset criterion.

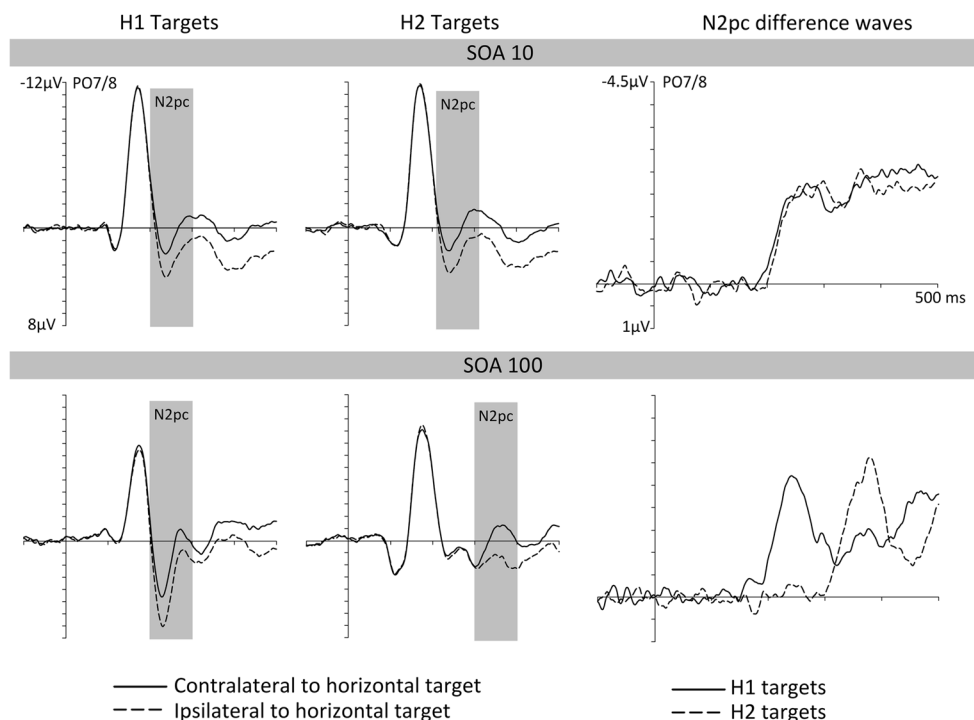


Fig. 2 N2pc components elicited by target objects in the SOA 10 and SOA 100 conditions of Experiment 1. *Left and middle panels:* Grand-average ERP waveforms measured in the 500 ms interval after the onset of the first search display at posterior electrodes PO7/PO8 contralateral

and ipsilateral to a horizontal target in the first display (H1 targets) or second display (H2 targets). *Right panel:* N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for H1 and H2 targets, and both SOA conditions

contralateral ERPs for H1 and H2 targets. ERPs are shown separately for the SOA 10 (top) and SOA 100 (bottom) condition. In both SOA conditions, clear N2pc components of similar size were elicited to both H1 and H2 targets. The onset latency differences of the N2pc components to H1 and H2 targets reflected the objective SOA between the two displays in the SOA 10 and SOA 100 conditions.

These observations were confirmed by analyses of N2pc mean amplitudes and onset latencies. In a repeated-measures ANOVA of N2pc mean amplitudes, with the factors display sequence (H1 vs. H2 targets), SOA (10 vs. 100 ms), and laterality (electrode contralateral vs. ipsilateral to the side of the horizontal target), a main effect of laterality, $F(1, 11) = 45.70, p < .001, \eta_p^2 = .81$, indicated that N2pc components were reliably elicited by horizontal target objects. There were no reliable effects of SOA, $F(1, 11) = 1.11, p = .315, \eta_p^2 = .09$, or display sequence, $F(1, 11) = 2.20, p = .183, \eta_p^2 = .16$, and no significant interactions between these two factors and laterality, both $F(1, 11) < 1.32, p > .276, \eta_p^2 < .12$, indicating that N2pc amplitudes did not differ systematically between SOA conditions, or between H1 and H2 targets. Follow-up t tests comparing contralateral with ipsilateral activity separately for H1 and H2 targets and both SOA conditions confirmed that all four N2pc components were reliably present, all $t(11) > 5.34, p < .001, d > .31$.

A repeated-measures ANOVA of N2pc onset latencies, with the factors SOA and display sequence, revealed a

significant interaction between these two factors, $F_c(1, 11) = 150.03, p < .001, \eta_p^2_c = .93$, showing that N2pc latency differences between H1 and H2 targets were more pronounced in the SOA 100 condition. A paired t test revealed that the N2pc to H2 targets emerged 121 ms later than the N2pc to H1 targets in this condition (324 ms vs. 203 ms after the onset of the first display), $t_c(11) = 17.56, p < .001, \eta_p^2_c = .97$. In the SOA 10 condition, the N2pc onset latency difference between H1 and H2 targets (214 vs. 219 ms) failed to reach significance, $t_c(11) = 1.29, p = .224, \eta_p^2_c = .13$.

N2pc components to targets with colour-matching and shape-matching distractors

Although the N2pc results shown in Fig. 2 suggest that two successively presented colour/shape targets can be selected rapidly and independently, they do not yet provide conclusive evidence for the rapid guidance of attention by colour/shape conjunctions. Target objects were accompanied either by a shape-matching or by a colour-matching distractor, and it remains theoretically possible that target selection was controlled exclusively by one of the two target-defining features, and thus operative only for one of the two displays on each trial. For example, a purely colour-based attentional guidance process would result in N2pc components only for displays with a horizontal target and a shape-matching distractor on opposite sides, but not for displays with two target-colour

objects (the target and a colour-matching distractor). The N2pc components shown in Fig. 2 could reflect the average across these two types of displays. To rule out this possibility, we computed N2pc components separately for targets accompanied by colour-matching and shape-matching distractors, separately for H1 and H2 targets and both SOA conditions. As can be seen in the resulting N2pc difference waveforms shown in Fig. 3, target N2pc components were not only present for horizontal displays that included shape-matching distractors but also for displays where targets and colour-matching distractors appeared on opposite sides. Paired t tests comparing contralateral and ipsilateral ERPs in the N2pc time windows confirmed that reliable target N2pc components were present both when targets were accompanied by colour-matching or by shape-matching distractors, for each combination of SOA condition and display sequence, all $t(11) > 3.93$, $p < .01$, $d > .27$. N2pc components were larger for targets accompanied by colour-matching distractors than for those in displays with shape-matching distractors (see Fig. 3). This was confirmed in a repeated-measures ANOVA of N2pc mean amplitudes, with the factors SOA condition, display sequence, laterality, and the new additional factor distractor type (colour-match vs. shape-match). This

ANOVA revealed a significant interaction between distractor type and laterality, $F(1, 11) = 11.93$, $p < .01$, $\eta_p^2 = .52$, reflecting the fact that targets triggered larger N2pcs when they appeared together with a colour-matching distractor than when they were accompanied by a shape-matching distractor.

Discussion

In Experiment 1, two targets defined by a conjunction of colour and shape appeared in two displays that were presented in rapid succession, with SOAs of 100 ms or 10 ms. The results obtained in this experiment provide no evidence that the allocation of attention to these two target objects operated in a serial fashion under these conditions. In fact, the temporal pattern of N2pc components to H1 and H2 targets was very similar to the results of previous studies where target selection could be based on a single feature, such as colour or shape (e.g., Eimer & Grubert, 2014b). As in these earlier studies, N2pc components of similar size were elicited by horizontal targets in the first and second display, and the onset latency difference between these two N2pc components approximately matched the objective SOA between the two displays. Critically, this was the case not only in the SOA 100 condition,

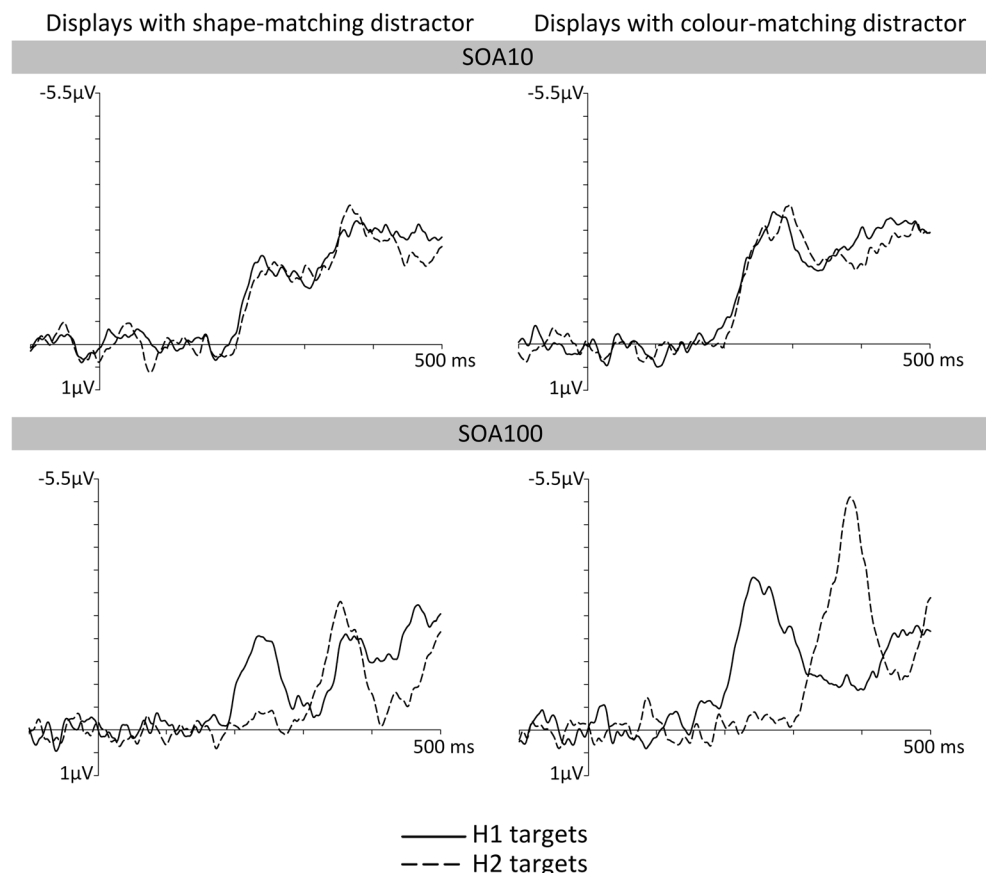


Fig. 3 N2pc difference waveforms obtained by subtracting ERPs ipsilateral to the target from contralateral ERPs in Experiment 1, shown separately for H1 and H2 targets that were accompanied by a

shape-matching distractor (*left panels*) or colour-matching distractor (*right panels*) in the SOA 10 condition and the SOA 100 condition

where the interval between the two displays may have been long enough to accommodate serial attention shifts between the two targets, but also in the SOA 10 condition. Here, the N2pc to H1 and H2 targets were identical in size and overlapped in time (see Fig. 2, top panels). This observation is inconsistent with the hypothesis that the attentional selection of two conjunctively defined targets always requires serial shifts of attention, so that attention can only be allocated to the second target after it has been withdrawn from its original location. This serial-selection scenario would also predict substantial performance costs for the SOA 10 relative to the SOA 100 condition. In fact, participants were more accurate with shorter SOAs, and there was also a tendency towards faster RTs in the SOA 10 condition. This pattern of behavioural results is most likely because in the SOA 10 condition, a sensory representation of the first target was still available when a visual representation of the second target is generated, so that gap locations of both targets could be directly compared. In the SOA 100 condition, the sensory representation of the first target shape may have already faded when the percept of the second target was created, and a stable working memory representation of this shape was not yet available, resulting in performance costs (see Brockmole, Wang, & Irwin, 2002; Dalvit & Eimer, 2011, for behavioural and ERP studies of perceptual and memory-based comparison processes across successive displays and how they are affected by the SOA between these displays).

The fact that N2pc to H1 and H2 targets were present regardless of whether targets were accompanied by shape-matching or by colour-matching distractors in the same display (see Fig. 3) demonstrates that target selection was not only based on one of the two target-defining features, and confirms that both colour and shape were involved in the parallel guidance of attention. The results of Experiment 1 thus provide clear evidence that attentional biases in favour of two target objects, presented in rapid succession, can be triggered independently and in parallel, even when these objects cannot be discriminated from distractors on the basis of a single visual feature but are defined by a conjunction of colour and shape. This raises the important question of how these spatially selective processing biases were generated. One possibility is that they emerged as the result of separate search templates for the target colour and the target shape that operated independently and in parallel. In displays where a target was accompanied by a colour-matching distractor on the opposite side, shape-based attentional guidance would result in a lateralised spatial bias for the target location, resulting in a target N2pc. Colour-based guidance would result in a bilateral bias, and two N2pc components over opposite hemispheres that cancel each other out. If these two guidance processes operated in parallel, their net result would be an N2pc contralateral to the target. An analogous

pattern can be predicted for displays where the target is presented together with a shape-matching distractor. In this case, the N2pc components observed in Experiment 1 would reflect the net spatial bias triggered by target objects because they always possess both template-matching features, whereas the distractor in the same display only has one of these features. An alternative possibility is that attention was guided by a single target object template that represents both target-defining features in an integrated fashion (e.g., blue circle). In this case, target objects will attract attention but partially matching distractors will not, because they do not match the integrated target object template. The N2pc components measured in Experiment 1 would therefore exclusively reflect the spatial bias triggered by target objects. Because N2pc components reflect relative differences in attentional biases between hemispheres, these two possibilities cannot be distinguished on the basis of the N2pc results of Experiment 1, where targets and partially matching distractors always appeared in the same display. To find out whether attentional allocation processes during search for colour/shape conjunction targets are controlled by separate feature templates for colour and shape or by an integrated object template, N2pc components need to be measured independently for targets and for colour-matching and shape-matching distractors. This was done in Experiment 2.

Experiment 2

As in Experiment 1, targets were defined by a specific colour/shape combination, and trials where a horizontal stimulus pair preceded or followed a vertical stimulus pair were randomly intermixed. The SOA between the two displays was always 10 ms. However, some displays now contained a colour-matching or shape-matching distractor, with a nontarget object without target-matching features on the opposite side. These displays were either preceded or followed by another display that contained a target and a task-irrelevant nontarget object (see Fig. 4). In addition to these one-target (1T) trials, there were also two-target (2T) trials with two successive displays that contained a target and a task-irrelevant nontarget object on opposite sides. Participants' task was to report the number of target objects. The temporal pattern of N2pc components to H1 and H2 targets was expected to be similar to the results observed in the SOA 10 condition of Experiment 1. The critical new question was whether horizontal shape-matching and colour-matching distractors would elicit N2pc components in 1T trials when they were preceded or followed by another display that included a vertical target. If attention was controlled by templates that represent targets as integrated objects, these partially matching distractors should not be able to attract attention and should therefore not trigger any N2pc. If the allocation of attention was guided in a

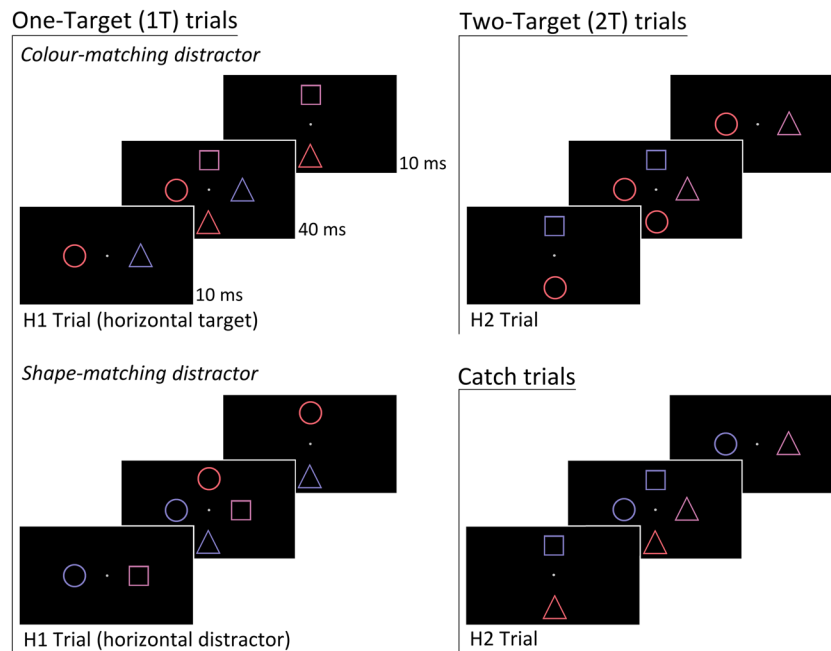


Fig. 4 Schematic illustration of the search displays and the time course of events in one-target (1T) trials, two-target (2T) trials, and catch trials of Experiment 2. In the examples shown, the target is the *red circle*. Participant's task was to report the number of targets (one or two) and refrain from responding on catch trials. On 1T trials, one display

contained the target and a task-irrelevant nontarget, and the other a colour-matching or shape-matching distractor with an irrelevant nontarget (shown separately). Displays with a horizontal target or distractor preceded vertical displays (H1 trials) or vice versa (H2 trials). (Colour figure online)

strictly feature-based fashion by separate colour and shape templates, N2pc components should not only be triggered by targets but also by colour-matching and shape-matching distractors. If colour-based and shape-based guidance processes operated in an entirely independent noninteractive way, target N2pc components should reflect the additive effects of the spatial biases triggered by target colours and shapes, and should therefore be identical to the sum of the two N2pc components triggered by colour-matching and shape-matching distractors.

Method

Participants

Thirteen participants were paid to take part in Experiment 2. One of them was excluded from analysis due to excessive eye-movement activity. The remaining 12 participants were aged between 20 and 38 years ($M = 29$, $SD = 5.39$). Nine were female; four were left-handed. All participants had normal or corrected-to-normal vision.

Stimuli and procedure

As in Experiment 1, stimuli were coloured outline shapes but no longer included any gaps. The possible stimulus colours were blue (CIE colour coordinates: .279/.265), purple (.365/.299), or red (.470/.340). All colours were

equiluminant (11.5 cd/m^2). As in Experiment 1, each participant was assigned a specific target shape/colour conjunction that remained constant throughout the experiment. In contrast to Experiment 1, each display now contained only one object with target-matching features (either the target or a partially matching distractor), which was always accompanied by a nontarget object without target-matching features on the opposite side. The other main difference to Experiment 1 was that trials could include either one or two target objects (see Fig. 4). In one-target trials, one of the two displays contained a target/nontarget pair, while the other contained a partially matching distractor/nontarget pair. In two-target trials, the two successive displays both contained a target/nontarget pair. There were also infrequent no-target catch trials, where both displays contained a partially matching distractor/nontarget pair. Participants' task was to report the number of targets presented in each trial (one or two) and to refrain from responding if no targets were detected (on catch trials).

Only the SOA 10 condition was tested in Experiment 2, which contained 24 blocks of 72 trials. In each block, there were 48 one-target (1T) trials, 16 two-target (2T) trials, and eight catch trials, which were presented in a randomly intermixed fashion. Note that "one target" responses were 3 times as likely as "two target" responses. Display sequence (horizontal display first or second: H1 or H2 trials, with horizontal displays containing either a target or a partially

matching distractor) and the temporal and spatial position of targets and partially matching distractors was randomly and independently determined on each trial. Each display was presented for 50 ms, and the interval between the offset of the second display and the onset of the first display on the next trial was 1,500 ms. All other aspects of procedure and stimulus presentation were identical to Experiment 1.

EEG recording and data analyses

All aspects of EEG recording and data analysis were identical to Experiment 1. Rejection of trials contaminated with artefacts, very slow or anticipatory responses, or incorrect or missing responses led to an exclusion of an average of 13.4% of all trials (12.4% and 11.8% in 1T trials with a horizontal target or partially matching distractor, respectively, and 17.5% in 2T trials). N2pc components were computed separately for target objects and for colour-matching and shape-matching distractor objects on the horizontal midline, separately for H1 and H2 trials, and for 1T and 2T trials. The time windows used for N2pc mean amplitude analyses were the same as in the SOA 10 condition of Experiment 1, and jackknife-based N2pc latency analyses were also identical to Experiment 1.

Results

Behavioural performance

There were no anticipatory or very slow RTs in Experiment 2. A repeated-measures ANOVA, with the factors trial type (1T vs. 2T trials) and display sequence (H1 vs. H2 targets) was run separately for RTs and for error rates. For RTs, there was a main effect of trial type, $F(1, 11) = 59.87, p < .001, \eta_p^2 = .85$, indicating faster RTs in the more frequent 1T trials relative to the less frequent 2T trials (504 ms vs. 567 ms). There was no effect of display sequence (536 ms for both H1 and H2 trials) and no interaction between both factors, both $F(1, 11) < 1.05, p > .834, \eta_p^2 < .01$. For error rates on target-present trials, a main effect of trial type, $F(1, 11) = 27.70, p < .001, \eta_p^2 = .72$, indicated that error rates were less frequent in 1T than in 2T trials (1.5% vs. 9.0%). The main effect of display sequence (3.9% and 3.6% for H1 and H2 trials, respectively) only approached significance, $F(1, 11) = 4.67, p = .054, \eta_p^2 = .30$, as did the interaction between both factors, $F(1, 11) = 4.06, p = .069, \eta_p^2 = .27$. The false-alarm rate on target-absent catch trials where there was no target present was 3.6%.

N2pc components to targets

Figure 5 (left and middle panels) shows ERPs for target-horizontal trials in an identical fashion to Experiment 1. Clear N2pc components were elicited by H1 and H2 targets

on 1T as well as 2T trials, and N2pc latencies to H1 and H2 targets reflected the objective 10-ms SOA between the two displays (as shown in the right panel of Fig. 5, depicting difference waves obtained by subtracting ipsilateral from contralateral ERPs). A repeated-measures ANOVA of N2pc mean amplitudes, with the factors trial type (1T vs. 2T), display sequence (H1 vs. H2 target), and laterality (electrode contralateral vs. ipsilateral to the side of the horizontal target), revealed a main effect of laterality, $F(1, 11) = 67.16, p < .001, \eta_p^2 = .86$, indicating that N2pc components were reliably elicited by horizontal target items. There was a significant interaction between trial type and laterality, $F(1, 11) = 13.87, p < .01, \eta_p^2 = .56$, as N2pc components were generally larger on 2T than on 1T trials (as shown in Fig. 5). None of the interactions involving the factor display sequence reached significance, all $F(1, 11) < .20, p > .665, \eta_p^2 < .02$. Follow-up *t* tests comparing contralateral with ipsilateral activity in response to H1 and H2 targets separately for 1T and 2T trials confirmed that all four N2pc components were reliably present, all $t(11) > 6.86, p < .001, d > .55$. For N2pc onset latency values, a repeated-measures ANOVA, with the factors trial type and display sequence, revealed a main effect of display sequence, $F_c(1, 11) = 20.71, p < .001, \eta_p^2 = .65$, demonstrating that N2pc components to H2 targets were reliably delayed relative to the N2pc to H1 targets by about 15 ms (201 ms vs. 185 ms for 1T trials; 202 ms vs. 188 ms for 2T trials).

N2pc components to partially matching distractors

Figure 6 shows ERPs measured on 1T trials that included a vertical target in one display and a horizontal colour-matching or shape-matching distractor in the other display. Clear N2pc components were elicited by both types of horizontal partially matching distractors in the first and second display (H1 and H2 trials). A repeated-measures ANOVA conducted on N2pc mean amplitudes, with the factors distractor type (shape-match vs. colour-match), display sequence (H1 vs. H2 distractor), and laterality (electrode contralateral vs. ipsilateral to the side of the horizontal distractor), revealed a main effect of laterality, $F(1, 11) = 52.86, p < .001, \eta_p^2 = .83$, indicating that N2pc components were reliably elicited in response to these partially matching distractors. There were no reliable interactions between laterality and display sequence, $F(1, 11) = .00, p = .960, \eta_p^2 = .00$, or between laterality and distractor type, $F(1, 11) = 1.50, p = .246, \eta_p^2 = .12$, suggesting that N2pc amplitudes did not differ between H1 and H2 distractors, or between colour-matching and shape-matching distractors. Follow-up *t* tests comparing contralateral with ipsilateral activity separately for H1 and H2 trials and both types of partially matching distractors confirmed that all four N2pc components were reliably present, all $t(11) > 4.41, p < .01, d > .23$.

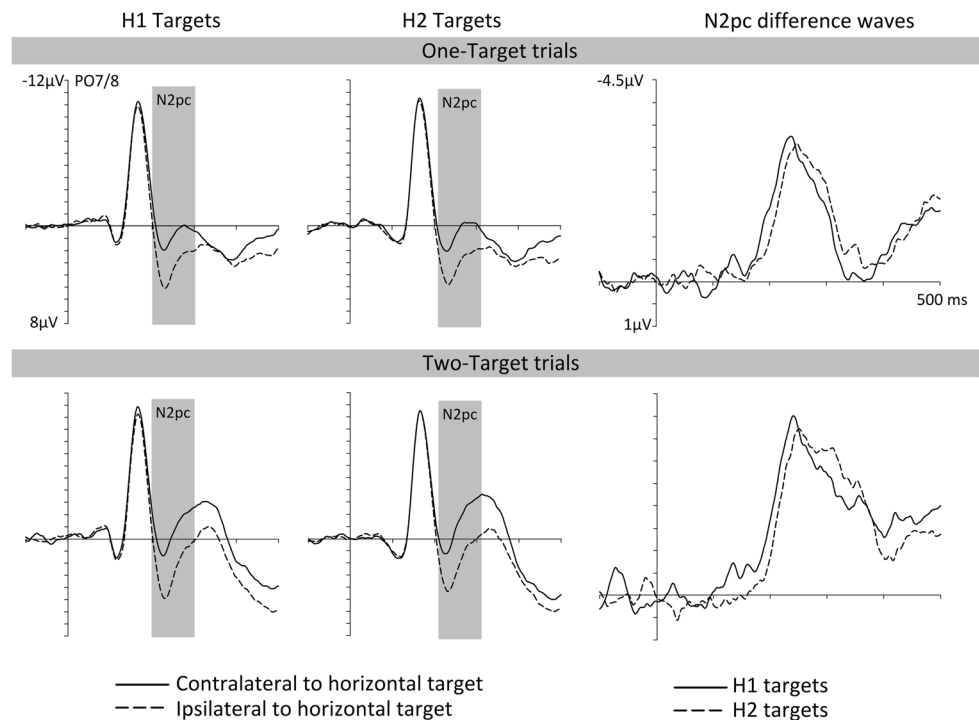


Fig. 5 N2pc components elicited by target objects on one-target (1T) and two-target (2T) trials in Experiment 2. *Left and middle panels:* Grand-average ERP waveforms measured in the 500 ms interval after the onset of the first search display at posterior electrodes PO7/PO8 contralateral

and ipsilateral to a horizontal target in the first display (H1 targets) or second display (H2 targets). *Right panel:* N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for H1 and H2 targets, and for 1T and 2T trials

N2pc components to targets and partially matching distractors

Finally, we directly compared N2pc components to targets and to partially matching distractors. These analyses included N2pcs measured in response to colour-matching and shape-matching distractors in 1T trials, and target N2pc components observed in 2T trials, because these two types of trials both contained a target object in the other (vertical) display. N2pc components to targets were larger than N2pc components to partially matching distractors (as is evident when comparing Figs. 5 and 6). Repeated-measures ANOVAs conducted separately for targets versus colour-matching or shape-matching distractors on H1 or H2 trials confirmed that target N2pc amplitudes were significantly larger than N2pc amplitudes to shape-matching or colour-matching distractors, all $F(1, 11) > 23.89$, $p < .001$, $\eta_p^2 > .68$.

Do the N2pc components triggered by target objects simply reflect the additive contributions of the N2pc components to colour-matching and shape-matching distractors, or are target N2pc amplitudes larger than the sum of the two N2pcs to these two types of distractors? To answer this question, we averaged N2pc components across H1 and H2 trials (after aligning them temporally to the onset of the respective horizontal display, which was 10 ms later on H2 trials), separately for target objects on 2T trials and for colour-matching and shape-matching distractors on 1T trials. Next, N2pc components

triggered by colour-matching and shape-matching distractors were summed, and compared to the N2pc elicited by target objects. The resulting N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs are shown in Fig. 7. The summed N2pc response to colour-matching and shape-matching distractors was initially very similar to the target N2pc, up to approximately 230 ms after display onset. Beyond this point in time, the N2pc to target objects became larger than the summed N2pc to the two types of distractors (i.e., superadditive). We employed two procedures to formally test when the target N2pc became larger than the summed contribution of the N2pcs to colour-matching and shape-matching distractors. First, the summed N2pc difference waveform for partially matching distractors was subtracted from the N2pc difference wave for targets, separately for each participant, followed by a jackknife-based analysis of these double subtraction waveforms with an onset criterion of $-0.5 \mu\text{V}$. This analysis showed that N2pc amplitudes to targets became larger than the summed N2pcs to partially matching distractors at 232 ms after display onset. In an independent second analysis, we conducted successive one-tailed paired t tests comparing individual N2pc difference waves for targets, and summed partially matching distractors for each consecutive 2-ms sampling point after display onset. A significant amplitude difference between these two waveforms had to remain present for at least five consecutive subsequent sampling points (corresponding to 10 ms) in order to be

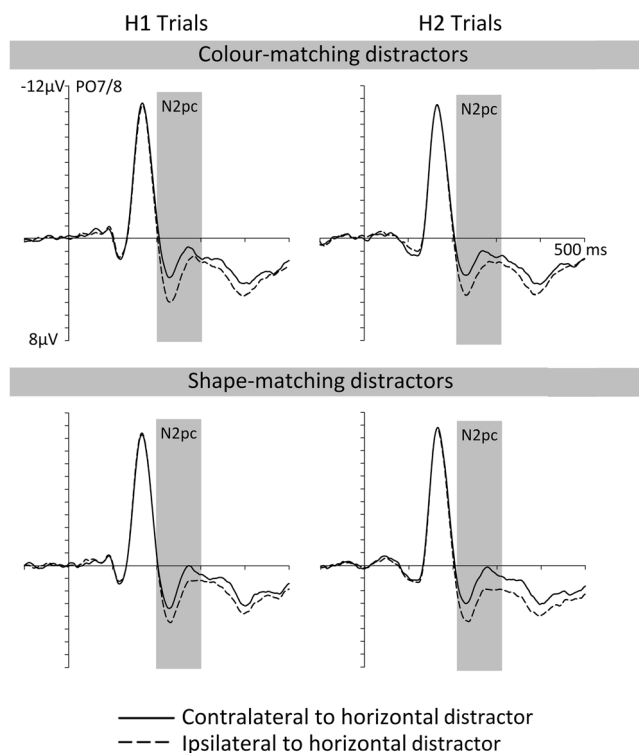


Fig. 6 N2pc components elicited in Experiment 2 on 1T trials by horizontal colour-matching or shape-matching distractors. Grand-average ERP waveforms measured in the 500 ms interval after the onset of the first search display at posterior electrodes PO7/PO8 contralateral and ipsilateral to a horizontal partially matching distractor are shown separately for trials where the distractor appeared in the first display (H1 distractor) or second display (H2 distractor)

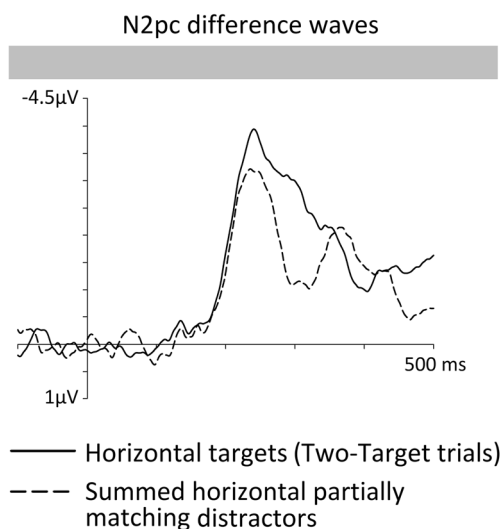


Fig. 7 N2pc difference waveforms obtained in Experiment 2 by subtracting ipsilateral from contralateral ERPs. These difference waves were collapsed across H1 and H2 trials, after temporal alignment to the onset of the horizontal display on these trials. The *solid line* shows the N2pc component triggered by horizontal target objects on 2T trials. The *dashed line* shows the sum of the two N2pc components elicited by horizontal colour-matching and shape-matching distractors on 1T trials. (See text for details)

interpreted as marking the onset of a superadditive target N2pc component. This procedure yielded an onset estimate of 234 ms poststimulus (with *p* values of .040, .029, .019, .014, and .014 in the 10-ms time period, from 234 ms to 244 ms, respectively), which matched the result from the jackknife-based analysis almost perfectly.

Discussion

The N2pc results obtained in Experiment 2 rule out the hypothesis that the attentional selection of targets defined by a conjunction of colour and shape is guided by templates that represent targets as fully integrated objects. If this was the case, colour-matching or shape-matching distractors should not have been able to attract attention and to trigger N2pc components. In fact, horizontal colour-matching and shape-matching distractors elicited clear N2pc components on 1T trials where they were preceded or followed by a vertical target in the other display (see Fig. 6). The presence of N2pc components to partially matching distractors shows that the attentional processing biases triggered during colour/shape conjunction search are at least in part controlled by processes that operate in a feature-specific fashion, irrespective of the presence or absence of the other target attribute.

N2pc components to targets were larger than the N2pcs triggered by colour-matching and shape-matching distractors, in line with the possibility that target N2pcs reflect the additive effects of independently operating colour-based and shape-based guidance processes. Direct comparisons between the sum of the N2pcs to these two types of partially matching distractors and target N2pc amplitudes revealed that this was indeed the case for the early phase of the N2pc, up to around 230 ms after display onset (see Fig. 7). During this phase, attentional processing biases were apparently generated in a local fashion by independent feature-specific guidance processes. Beyond this time point, the target N2pc was larger than the sum of the two N2pcs to partially matching distractors, suggesting that attentional guidance was no longer exclusively feature-based (see below for further discussion).

In addition to the presence of N2pc components to colour-matching and shape-matching distractors, Experiment 2 also revealed a pattern of target N2pc components that was similar to the SOA 10 condition of Experiment 1. Temporally overlapping N2pc components of similar size were triggered by H1 and H2 targets, both on 1T and 2T trials (see Fig. 5). The onset latency differences between N2pcs to H1 versus H2 targets (about 15 ms) closely matched the objective 10 ms between the two displays. In contrast to Experiment 1, this latency difference was significant, and target N2pc amplitudes were substantially larger in Experiment 2 (compare Figs. 2 and 5). As discussed below, these differences are likely to reflect the fact that targets were accompanied in the same display by partially matching distractor objects in

Experiment 1 but by objects without template-matching features in Experiment 2.

In line with the assumption that the two targets in the two successive displays were selected independently and in parallel, there was no evidence that the presence of a vertical target in the second display attenuated the N2pc to horizontal targets on 2T trials relative to 1T trials where only a single target was present. In fact, the opposite was the case, as target N2pc components were larger on 2T trials as compared to 1T trials (see Fig. 5). The factors responsible for this unexpected result are not clear. One possibility is that 1T trials were much more frequent than 2T trials, which may have resulted in an increased attentional bias towards targets when two target objects appeared unexpectedly in rapid succession. Another possibility that needs to be investigated in future experiments is that the near-simultaneous presentation of two identical target objects magnifies the attentional response to both of them, relative to trials where only a single target is present.

General discussion

The current study measured N2pc components to track the allocation of attention to two target objects in two displays that were presented in rapid succession. Previous studies using similar rapid sequential presentation procedures with feature-defined targets have shown that attention is allocated rapidly and in parallel to both target objects, with each selection process following its own independent time course (Eimer & Grubert, 2014b; Grubert & Eimer, 2015, 2016; Jenkins et al., 2016). In contrast to these earlier experiments, target objects were now defined by a specific combination of colour and shape. According to Feature Integration Theory (e.g., Treisman, 1988; Treisman & Gelade, 1980), the identification of such targets is based on the integration of information across feature dimensions, which requires focal attention that can only be allocated serially to one object at a time. The Guided Search model (Wolfe, 2007) also assumes that attentional object selection processes during conjunction search operate in a sequential fashion. If this was the case, the temporal pattern of N2pc components elicited by the two target objects in the present study should be different to the pattern found previously, when targets and nontargets could be distinguished on the basis of a single feature. In fact, the N2pc results obtained in Experiment 1 were very similar to results found in these earlier studies, in spite of the fact that targets were always accompanied by a colour-matching or shape-matching distractor in the same display, and could therefore not be selected on the basis of a unique target-defining feature. The observation that targets in the first and second display both elicited N2pc components of similar size, and the fact that these two components overlapped in time when the SOA between the two displays was 10 ms shows that spatial biases

for both target objects developed rapidly and independently, in line with the assumption that attention was allocated in parallel to both objects.

Experiment 2 investigated whether the parallel attentional processing biases for two conjunctively defined target objects revealed in Experiment 1 were the result of a single integrated object template, or of independent feature-specific search templates for colour and shape. Horizontal colour-matching and shape-matching distractors that appeared together, with a non-target in the same display, both elicited reliable N2pcs, demonstrating that they were able to attract attention. This observation rules out the possibility that attentional selectivity was entirely controlled by search templates that represent target features in an integrated object-based fashion. During the initial phase of the N2pc until about 230 ms after display onset, the sum of the two N2pc components to partially matching distractors was identical to the N2pc triggered by targets. During this time window, the attentional processing biases reflected by the N2pc were generated entirely independently by colour and shape templates, with target N2pcs reflecting the joint contribution of these feature-specific guidance processes.

If attentional selection processes are initially guided exclusively in a feature-specific fashion, thereby allowing partially matching distractors to attract attention and elicit N2pc components, as shown in Experiment 2, this implies that the target N2pc components observed in Experiment 1 do not exclusively reflect the attentional selection of these target objects but, instead, the difference between the spatial biases elicited simultaneously in opposite hemispheres by targets and by colour-matching or shape-matching distractors in the same display. In Experiment 2, targets were always accompanied by objects without any target-matching features, and N2pc components to target objects will therefore reflect the pure spatial bias triggered by these objects. If this is correct, target N2pc components should be larger in Experiment 2 relative to Experiment 1. A comparison of N2pc components to H1 and H2 targets elicited in the SOA 10 conditions of Experiment 1 (see Fig. 2, top panels) and Experiment 2 (see Fig. 5, top panels) shows that this was indeed the case. A post hoc analysis of target N2pc mean amplitudes in Experiment 1 (SOA 10 condition) and Experiment 2, with laterality and display sequence as within-participants factors, and experiment as between-participants factor, confirmed this observation. There was a significant interaction between laterality and experiment, $F(1, 22) = 7.89$, $p < .05$, $\eta_p^2 = .26$, reflecting the presence of attenuated N2pc components in Experiment 1 as compared to Experiment 2. This provides additional support for the hypothesis that rapid parallel feature-guided attentional biases were triggered concurrently in opposite hemispheres by targets and partially matching distractors in Experiment 1.

In Experiment 2, target N2pc amplitudes became superadditive (i.e., larger than the sum of the N2pcs to

colour-matching and shape-matching distractors) beyond 230 ms. A similar temporal pattern of N2pc amplitudes was observed in several of our previous studies investigating visual search for conjunctively defined target objects. In these experiments, search displays could contain a target, a distractor that matched one but not the other target-defining feature, or both the target and a partially matching distractor. Targets were defined by a combination of colour and shape (Eimer & Grubert, 2014a), a combination of two colours (Berggren & Eimer, 2016), or a combination of colour and alphanumerical category (Nako et al., 2016). In all of these tasks, target N2pc amplitudes initially equalled the sum of the N2pcs to the two partially matching distractors and became superadditive at some point between 220 and 250 ms after search display onset. Interestingly, a very similar temporal pattern of additive, followed by superadditive ERP modulations in response to target-defining features and feature conjunctions, was found in a study by Anllo-Vento, Schoenfeld, and Hillyard (2004) for displays that contained only a single stimulus at fixation. These stimuli were vertical or horizontal bar gratings that were either orange or red, and participants had to attend to one specific colour/orientation combination. Stimuli with the attended orientation and attended colour both elicited a posterior selection negativity (SN), which is observed in nonsearch tasks, where each display contains a single object with attended features (e.g., Anllo-Vento, Luck, & Hillyard, 1998). Importantly, the SN elicited by target objects that matched both the task-relevant bar orientation and colour was initially identical in amplitude to the sum of the two SN components triggered by the colour-matching and orientation-matching nontargets. Beyond 225 ms, SN amplitudes to targets became superadditive. This result was interpreted by Anllo-Vento et al. as demonstrating that, at this point in time, attentional selection processes became sensitive to the presence of the target-defining feature conjunction. In contrast to the N2pc, which reflects a lateralised bias of visual processing elicited by task-relevant features or objects in the left or right visual field, the SN components reported by Anllo-Vento et al. were not lateralised, because they were triggered in response to single objects at fixation. In spite of this difference, the observation that a superadditive attentional bias for conjunctively defined target objects emerges at almost exactly the same point in time for both components is intriguing, since it suggests that similar attentional selection processes may be operative in single-stimulus and multiple-stimulus visual displays. The onset of superadditive N2pc and SN components to conjunctively defined targets may mark the point in time where attentional biases are no longer generated in an entirely feature-specific fashion, but start to be affected by the joint presence of different target-defining features in the same object. The fact that this superadditivity was observed in the present Experiment 2, where the critical display was

immediately preceded or followed within 10 ms by another display that contained a vertical target object, suggests that such processing biases for feature conjunctions can be triggered in parallel for different objects in the visual field.

In Experiment 2, the N2pc to horizontal targets was compared to the sum of the two N2pc components to horizontal shape-matching and colour-matching distractors elicited on trials where the other display contained a vertical target object (see Fig. 7). A potential problem with this approach is that by adding the N2pcs to partially matching distractors, any impact of the vertical target object on these N2pcs is also included twice in the resulting summed waveforms. The observation that the target N2pc initially equalled the sum of the two N2pcs to partially matching distractors shows that up to about 230 ms poststimulus, vertical targets in the other display had no impact on the attentional biases triggered by these distractors, in line with the assumption that these biases were triggered in a local feature-based fashion. However, the presence of vertical targets in the other display may have contributed to the reduction of summed N2pc amplitudes to these distractors beyond this point in time. Although this possibility cannot be ruled out entirely, it is important to note that previous N2pc studies of conjunction search (e.g., Berggren & Eimer, 2016; Eimer & Grubert, 2014a) found analogous sequences of additive followed by superadditive target N2pc components for displays where targets and partially matching nontargets appeared without a potentially competing target-matching object on the vertical midline. Furthermore, as described earlier, Anllo-Vento et al. (2004) found a nearly identical temporal sequence of additive followed by superadditive SN components for conjunctively defined target objects in single-stimulus displays. The similarity between these previous findings and the results of the current Experiment 2 suggests that competitive influences from vertical targets on N2pcs to partially matching distractors are unlikely to be the main cause of the superadditivity of target N2pcs observed beyond 230 ms poststimulus.

What are the general implications of the current results for the nature of attentional mechanisms in conjunction search tasks? The current N2pc results demonstrate that attentional biases for target features and objects can be triggered in parallel and independently at different locations in the visual field. However, it could be argued that the presence of such spatially selective processing biases does not provide sufficient evidence to conclude that attentional selection operates in parallel during conjunction search. One central finding of the current study was that these biases were initially triggered independently and in parallel by target colours and target shapes, and contributed additively to the early phase of the N2pc component in the present experiments. This is very much in line with previous research on feature-based attention

in humans and nonhuman primates, which has demonstrated that currently task-relevant features trigger attentional modulations of visual processing in a spatially global fashion across the visual field (e.g., Martinez-Trujillo & Treue 2004; Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007), even when attention and eye gaze are directed elsewhere (Bichot, Rossi, & Desimone, 2005). Visual processing modulations produced by feature-based attention can occur simultaneously at multiple locations in the visual field (Andersen, Hillyard, & Müller, 2008; Andersen, Müller, & Hillyard, 2015), as was the case for the parallel colour-based and shape-based attentional biases found in Experiment 2. It is often assumed that feature-based attention and attentional object selection are separate processes. For example, feature-based attention may highlight the locations of potentially task-relevant features during visual search, thereby providing guiding signals for a subsequent serial object selection stage (e.g., Bichot et al., 2005; Maunsell & Treue, 2006). Such suggestions are based on the traditional two-stage architecture of visual processing (e.g., Broadbent, 1958), which assumes a fundamental division between early parallel automatic processes (including spatially global feature-based attention) and later serial controlled processes, with attentional selection marking the transition between these two types of processing. If feature-based attention and attentional selection are separate processing stages, the presence of parallel feature-based attentional modulations for multiple objects cannot be used to draw conclusions about the nature of attentional object selection processes during conjunction search. An alternative is to reject the standard two-stage architecture and to describe attentional selection instead as a temporally extended process where visual processing biases for task-relevant features and objects (as reflected by N2pc components) develop continuously in real time. Such attentional biases can initially be generated in parallel at multiple locations but may then become more selective, due to competitive interactions between objects at different levels of the visual processing hierarchy (e.g., Desimone & Duncan, 1995; Duncan, 2006). Within this alternative conceptual framework, attentional selectivity refers to the presence of such visual processing biases at a particular time point, with spatially global effects of feature-based attention and subsequent biases that are sensitive to the presence of feature conjunctions reflecting different phases of selective attentional processing at different moments in time (see Eimer, 2014, 2015, for further discussion). In this context, the current results show that both types of biases can be elicited in parallel by multiple objects during conjunction search.

A final important conceptual issue concerns the role of display size for the efficiency of conjunction search. In the present study, each of the two successive displays only contained two objects on opposite sides, and participants had to select two out of these four objects as targets. As shown by the N2pc results for Experiment 1, attentional biases for

conjunctively defined target objects were triggered rapidly and in parallel, even though these targets were accompanied by a single partially matching distractor in each display. It is well known that the efficiency of conjunction search decreases as the number of partially target-matching distractor objects increases (e.g., Wolfe, 1998). Because these distractors all have the potential to elicit feature-based attentional processing biases, adding more of them to the same display will reduce the net attentional bias towards the target and therefore make target-distractor discriminations more difficult. According to a recent suggestion by Hulleman and Olivers (2017), the difficulty of these discriminations determines the size of the functional viewing field (FVF)—the area within which attentional selection processes operate in parallel during any given fixation period. When conjunction search becomes more difficult because more partially matching distractors are added, the size of each FVF decreases, resulting in more eye movements and longer search times. In the present study, where each display was presented for 50 ms and eye movements were not allowed, all objects had to be processed within a single fixation, and therefore all needed to be included within the same FVF. The time course of the attentional selection processes revealed by the temporal pattern of N2pc components therefore reflects the guidance of attention during conjunction search within a single fixation episode where the FVF included all display stimuli. Increasing the number of partially matching distractors in each of the two successively presented displays will decrease the size of the FVF, up to the point where it no longer includes both target objects. Under these conditions, the two targets may no longer be detectable within a single fixation episode, resulting in increased error rates and attenuated target N2pc components, which may specifically affect the N2pc to targets in the second display. These predictions will need to be assessed in future experiments.

In summary, the current study has demonstrated that two target objects defined by a conjunction of colour and shape and presented in rapid succession trigger parallel and independent attentional biases of visual processing. Initially, these biases are entirely feature-based and are elicited separately for target-matching colours and shapes. During a subsequent phase, they become sensitive to the joint presence of target features in the same object. These findings show that the guidance of attentional object selection during conjunction search is based on spatially selective processing biases for objects with task-relevant features or feature combinations that emerge simultaneously and independently at different locations in the visual field.

Acknowledgements This research was supported by Grants ES/K006142/1 and ES/L016400/1 from the Economic and Social Research Council, United Kingdom. The authors thank Soeren Andersen, John McDonald, and an anonymous referee for their comments.

References

- Andersen, S. K., Hillyard, S. A., & Müller, M. M. (2008). Attention facilitates multiple stimulus features in parallel in human visual cortex. *Current Biology*, *18*, 1006–1009.
- Andersen, S. K., Müller, M. M., & Hillyard, S. A. (2015). Attentional selection of feature conjunctions is accomplished by parallel and independent selection of single features. *Journal of Neuroscience*, *35*(27), 9912–9919.
- Anllo-Vento, L., Luck, S. J., & Hillyard, S. A. (1998). Spatio-temporal dynamics of attention to color: Evidence from human electrophysiology. *Human Brain Mapping*, *6*, 216–238.
- Anllo-Vento, L., Schoenfeld, M. A., & Hillyard, S. A. (2004). Cortical mechanisms of visual attention: Electrophysiological and neuroimaging studies. In M. I. Posner (Ed.), *Cognitive neuroscience of attention* (pp. 180–193). New York: Guilford Press.
- Berggren, N., & Eimer, M. (2016). The control of attentional target selection in a colour/colour conjunction task. *Attention, Perception, & Psychophysics*, *78*, 2383–2396.
- Bichot, N. P., Rossi, A. F., & Desimone, R. (2005). Parallel and serial neural mechanisms for visual search in macaque area V4. *Science*, *308*, 529–534.
- Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon Press.
- Brockmole, J., Wang, R., & Irwin, D. (2002). Temporal integration between visual images and visual percepts. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 315–334.
- Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences*, *9*, 349–354.
- Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale: Erlbaum.
- Dalvit, S., & Eimer, M. (2011). Memory-driven attentional capture is modulated by temporal task demands. *Visual Cognition*, *19*, 145–153.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222.
- Duncan, J. (2006). EPS Mid-Career Award 2004: Brain mechanisms of attention. *The Quarterly Journal of Experimental Psychology*, *59*, 2–27.
- Duncan, J., & Humphreys, G. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458.
- Egeth, H., Virzi, R., & Garbart, H. (1984). Searching for conjunctively defined targets. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 32–39.
- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*, 225–234.
- Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences*, *18*, 526–535.
- Eimer, M. (2015). EPS Mid-Career Award 2014: The control of attention in visual search—Cognitive and neural mechanisms. *The Quarterly Journal of Experimental Psychology*, *68*, 2437–2463.
- Eimer, M., & Grubert, A. (2014a). The gradual emergence of spatially selective target processing in visual search: From feature-specific to object-based attentional control. *Journal of Experimental Psychology: Human Perception and Performance*, *40*, 1819–1831.
- Eimer, M., & Grubert, A. (2014b). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, *24*, 193–198.
- Eimer, M., Kiss, M., & Nicholas, S. (2011). What top-down task sets do for us: An ERP study on the benefits of advance preparation in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 1758–1766.
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191.
- Grubert, A., & Eimer, M. (2015). Rapid parallel attentional target selection in single-color and multiple-color visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *41*, 86–101.
- Grubert, A., & Eimer, M. (2016). Rapid attentional selection processes operate independently and in parallel for multiple targets. *Biological Psychology*, *121*, 99–108.
- Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience*, *21*, 760–775.
- Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience*, *18*, 604–613.
- Hopf, J. M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., & Heinze, H. J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex*, *10*, 1233–1241.
- Hulleman, J., & Olivers, C. N. (2017). The impending demise of the item in visual search. *Behavioral and Brain Sciences*, *40*, 1–69.
- Jenkins, M., Grubert, A., & Eimer, M. (2016). Rapid parallel attentional selection can be controlled by shape and alphanumeric category. *Journal of Cognitive Neuroscience*, *28*, 1672–1687.
- Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1000–1014.
- Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-based attention increases the selectivity of population responses in primate visual cortex. *Current Biology*, *14*, 744–751.
- Maunsell, J. H., & Treue, S. (2006). Feature-based attention in visual cortex. *Trends in Neurosciences*, *29*, 317–322.
- Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology*, *35*, 99–115.
- Nako, R., Grubert, A., & Eimer, M. (2016). Category-based guidance of spatial attention during visual search for feature conjunctions. *Journal of Experimental Psychology: Human Perception and Performance*, *42*, 1571–1586.
- Niebergall, R., Khayat, P. S., Treue, S., & Martinez-Trujillo, J. C. (2011). Multifocal attention filters targets from distracters within and beyond primate MT neurons' receptive field boundaries. *Neuron*, *72*, 1067–1079.
- Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, *15*, 327–334.
- Saenz, M., Buracas, G. T., & Boynton, G. M. (2002). Global effects of feature-based attention in human visual cortex. *Nature Neuroscience*, *5*, 631–632.
- Serences, J. T., & Boynton, G. M. (2007). Feature-based attentional modulations in the absence of direct visual stimulation. *Neuron*, *55*, 301–312.
- Treisman, A. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology*, *40*, 201–237.
- Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97–136.
- Ulrich, R., & Miller, J. O. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology*, *38*, 816–827.
- Wolfe, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review*, *1*, 202–238.
- Wolfe, J. M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, *9*, 33–39.
- Wolfe, J. M. (2007). Guided Search 4.0: Current progress with a model of visual search. In W. Gray (Ed.), *Integrated models of cognitive systems* (pp. 99–119). New York: Oxford University Press.

- Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, *400*, 867–869.
- Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception & Performance*, *29*, 121–138.