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Rapid attentional selection processes operate independently and in parallel for multiple targets

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ABSTRACT

The question whether multiple objects are selected serially or in parallel remains contentious. Previous studies employed the N2pc component as a marker of attentional selection to show that multiple selection processes can be activated concurrently. The present study demonstrates that the concurrent selection of multiple targets reflects genuinely parallel processing that is unaffected by whether or when an additional selection process is elicited simultaneously for another target. Experiment 1 showed that N2pc components triggered during the selection of a colour-defined target were not modulated by the presence versus absence of a second target that appeared in close temporal proximity. Experiment 2 revealed that the same rapid parallel selection processes were elicited regardless of whether two targets appeared simultaneously or in two successive displays. Results show that rapid attentional selection processes within the first 200 ms after stimulus onset can be triggered in parallel for multiple objects in the visual field.

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1. Introduction

During the processing of visual scenes, multiple objects compete for access to visual perception and conscious awareness, and only some of these objects succeed in winning this competition by attracting attention. The question whether visual attention can be directed simultaneously to different objects or is always allocated to a single object at a time is still under dispute. Serial models of visual search (e.g., Treisman & Gelade, 1980; Wolfe, 1994, 2007) assume that objects are selected sequentially, and that attention has to be de-allocated from its previous location before it can be directed to a new visual object. In contrast, parallel models of visual attention (e.g., Desimone & Duncan, 1995) and multiple object tracking (e.g., Cavanagh & Alvarez, 2005) postulate that attention can be simultaneously allocated to several objects in a visual scene.

To assess the serial versus parallel selection of visual objects, the deployment of attention in visual scenes with multiple objects needs to be measured continuously in real time. Event-related brain potentials (ERPs) can track the time course of attentional selection processes on a millisecond-by-millisecond basis. The N2pc is a lateralised ERP component that marks the allocation of focal attention to candidate target objects in visual search (e.g., Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999). This component typically emerges 180–200 ms after stimulus onset at posterior electrodes contralateral to the visual field where a possible target object is presented, is generated in extrastriate areas of the ventral visual stream (Hopf et al., 2000), and is assumed to reflect the spatially selective enhancement of visual processing at particular retinotopic locations within these areas (see Eimer, 2014, 2015, for details). In most N2pc studies of attentional target selection, stimulus displays contain a single candidate target object among multiple task-irrelevant distractors. To employ the N2pc in investigations of the serial versus parallel nature of attentional allocation processes, this component needs to be measured in tasks where multiple task-relevant objects have to be selected concurrently. Because the N2pc is a contralateral component that is triggered when target objects appear in the left or right visual field, this component is absent for targets on the vertical meridian above or below fixation (Eimer & Grubert, 2014; Eimer, Kiss, & Nicholas, 2011; Hickey, McDonald, & Theeuwes, 2006; Hickey, Di Lollo, & McDonald, 2009; Woodman & Luck, 1999). When a target on the horizontal meridian and another target on the vertical meridian appear simultaneously or in rapid succession, the N2pc exclusively reflects the attentional selection of the horizontal target, irrespective of the concurrent attentional selection of the other vertical target. With this horizontal/vertical target presentation procedure, N2pc components can be employed to investigate serial versus parallel attentional selection processes in tasks where multiple target objects have to be selected.

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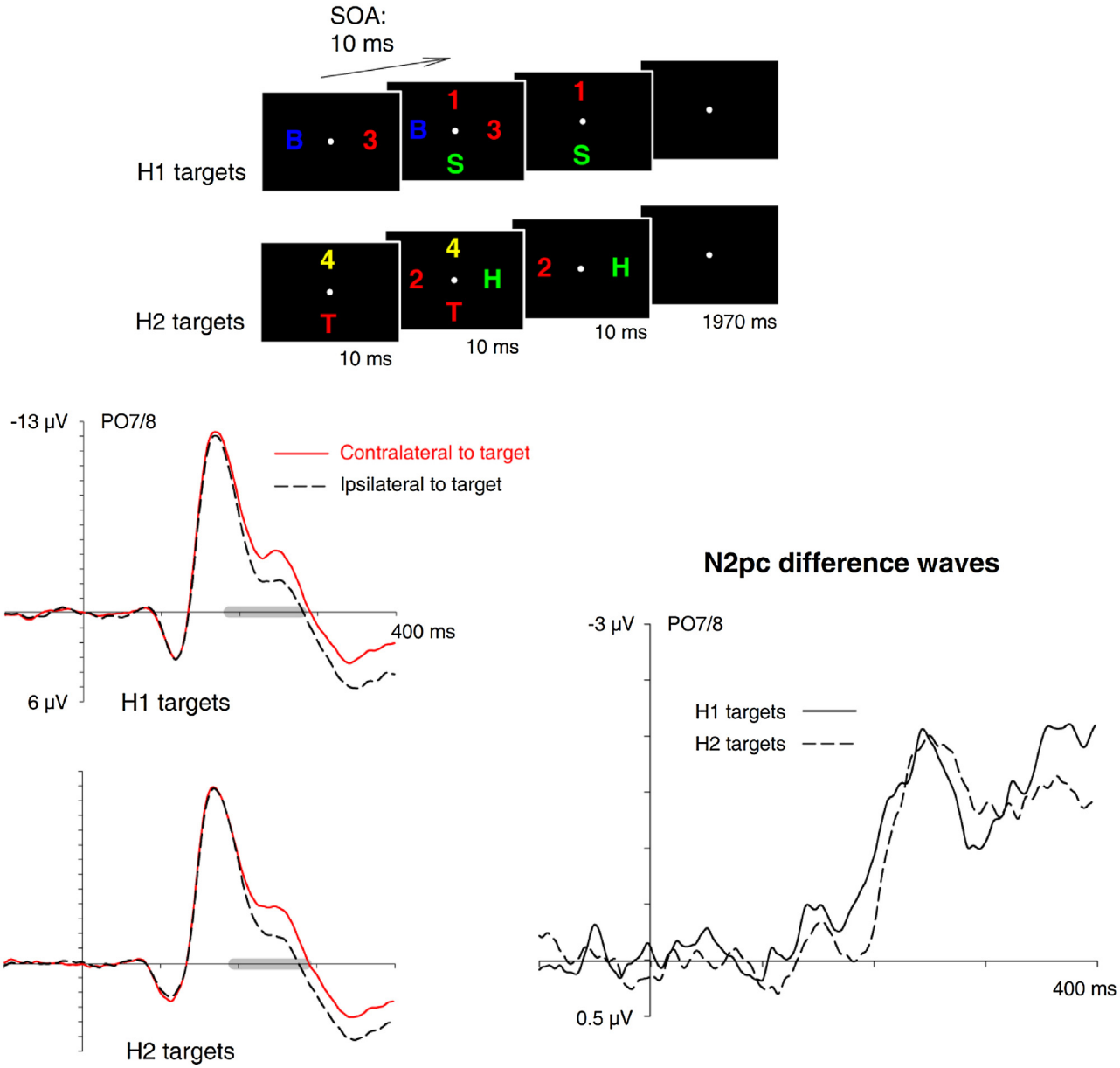

Fig. 1. Stimuli and previous N2pc results. Top panel: Schematic illustration of the time course of stimulus events in the study by Eimer and Grubert (2014). On each trial, two displays with a colour-defined target object (red in the example shown here) and a nontarget-colour distractor on opposite sides were presented sequentially for 20 ms. The SOA between the two displays was 10 ms (i.e., the two displays overlapped for 10 ms). The target/nontarget pair appeared on the horizontal meridian in one display and on the vertical meridian in the other display. Trials where the horizontal target appeared in the first display (H1 targets) or in the second display (H2 targets) were randomly intermixed. Participants had to judge the alphanumeric category of the two target objects (same/different). Bottom panel: ERP waveforms measured on trials with H1 and H2 targets at lateral posterior electrodes PO7/8 in the study by Eimer and Grubert (2014), and N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. N2pc components to H1 targets preceded N2pcs to H2 targets by about 10 ms. These N2pcs overlapped in time and were equal in size. The grey bars on the x-axis indicate N2pc time windows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In a recent N2pc study (Eimer & Grubert, 2014), we adopted this logic to demonstrate that focal attention can be allocated concurrently and independently to two sequentially presented target-colour objects. Two stimulus displays that each contained a colour-defined target item and a distractor item in a different nontarget colour on opposite sides were presented in rapid succession. All items were letters or digits. Participants' task was to identify the two target-colour items in the two consecutive displays, and to report whether their alphanumerical category was the same (both letters, both digits) or not (one letter and one digit). The target/nontarget pair in one display always appeared on the horizontal meridian (to the left and right of fixation), and the stimulus pair in the other display was presented on the vertical meridian (above and below fixation; Fig. 1, top panel). Trials where the horizontal display preceded the vertical display (horizontal target first: H1 targets) and trials where this order was reversed (horizontal target second: H2 targets) were randomly intermixed. Given these stimulation parameters, N2pc components reflected the attentional selection of the horizontal target on any given trial, irrespective of a second attentional selection process for the vertical target in the other display on the same trial. When the two search displays were separated by a stimulus asynchrony (SOA) of 10 ms, N2pc components of similar size were elicited on trials with H1 versus H2 targets, and these components overlapped in time (Fig. 1, bottom panel). The N2pc to H1 targets emerged 10 ms earlier than the N2pc to

H2 targets, and this onset latency difference matched the objective SOA between the two displays precisely.

These findings suggest that focal attention was allocated rapidly and in parallel to the two target objects in the first and second display, with each selection process following its own independent time course. If attentional selection processes had operated in a strictly sequential fashion, as postulated by serial models, attention shifts to targets in the second display would only have been initiated once attention had been disengaged from the first target. If this was the case, N2pc components on trials with H2 targets should have been substantially delayed relative to N2pcs to H1 targets, reflecting the sustained engagement of a serial attentional focus on the vertical target in the first display on these trials. It is possible that a serial focus of attention would be rapidly shifted from the first to the second target on each trial, immediately after the second display was presented. In this case, the N2pc to H1 targets should have been short-lived and much smaller than the N2pc to H2 targets, which was clearly not the case (see Fig. 1, bottom panel). The N2pc results observed in our previous study (Eimer & Grubert, 2014) are problematic for strictly serial attentional selection models, but are fully consistent with parallel models (see also Grubert & Eimer, 2015, and Jenkins, Grubert, & Eimer, in press, for additional evidence for similar rapid attentional allocation processes when sequentially presented targets were defined by two different colours, by a particular shape, or by their alphanumerical category).

However, the findings from these earlier N2pc studies do not necessarily provide conclusive evidence for fully independent parallel selection mechanisms. In these studies, each trial included two successively presented target objects in two different displays that were separated by a short SOA. The fact that H1 and H2 targets elicited temporally overlapping N2pc components shows that target objects in the first and second display were able to attract attention concurrently, contrary to the predictions of strictly serial selection models. However, a strong version of a parallel selection account does not only imply that multiple objects can be selected simultaneously, but also that these selection mechanisms operate entirely independently of each other. To provide support for such a strong parallel selection hypothesis, it has to be shown that the attentional selection of one particular target object remains completely unaffected by whether or when a concurrent selection process in response to another target at a different location is also activated.

The goal of the two experiments reported here was to provide such evidence. Both experiments included dual-target trials that were identical to our previous study (Eimer & Grubert, 2014; see Fig. 1). N2pc components elicited in these trials were compared to N2pcs measured in single-target trials where only one of the two successive displays contained a colour-defined target object (Experiment 1), and to simultaneous presentation trials where two targets and two distractor objects all appeared in the same search display (Experiment 2). In dual-target trials, two colour-defined target objects were presented successively in two displays that were separated by a 10 ms SOA. In one of the two displays, the target and a distractor object in a different nontarget colour appeared on opposite sides on the horizontal meridian. In the other displays, this pair of objects was presented on the vertical meridian. The order of these two displays (horizontal target first or second: H1 versus H2 targets) varied unpredictably across trials. Because the stimulus parameters in these dual-target sequential presentation trials were identical to our earlier study (Eimer & Grubert, 2014), these trials were expected to yield analogous N2pc results. The onset of the N2pc to H1 targets should precede the onset of the N2pc to H2 targets by approximately 10 ms, matching the objective SOA between the two displays. These two N2pc components should overlap in time and have similar amplitudes.

If the attentional selection of multiple colour-defined targets operated in a genuinely parallel fashion, the selection of a horizontal target on any given trial should be entirely independent from the concurrent selection of a vertical target object on the same trial. If this was the case, these selection processes should be elicited in exactly the same way, and thus yield identical N2pc components to H1 and H2 targets, regardless of whether a vertical target object was present or absent on these trials. This was tested in Experiment 1. Half of all trials in this experiment were dual-target trials, as described above. On the other randomly intermixed half of trials, only one of the two successively presented displays contained a target-colour item (single-target trials). This target was equally likely to be presented in the first or second display, and was equally likely to appear on the horizontal or vertical meridian. The same SOA between the two displays (10 ms) was employed on single-target and dual-target trials. Because half of all trials contained only a single target-colour item in Experiment 1, the same/different category discrimination task used in our previous study (Eimer & Grubert, 2014) could not be employed. Participants' task in Experiment 1 was to report on each trial whether one or two target-colour items were presented. N2pc components were computed in response to H1 and H2 targets, separately for single-target and dual-target trials. If the allocation of attention to horizontal target objects on dual-target trials was entirely independent from the concurrent attentional selection of vertical target objects in the other display, N2pc components to H1 and H2 targets on these trials should be identical in terms of their onset latencies and amplitudes to the corresponding N2pc components measured on single-target trials, where no vertical target object was present, and no second attentional selection process was activated. Such a result would provide strong evidence for independent parallel selection mechanisms. Because this type of evidence would essentially represent a confirmation of the null hypothesis (i.e., no N2pc differences between single-target and dual-target trials), we also calculated Bayes factors as measures of the likelihood that the null hypothesis is correct (see Rouder, Speckman, Sun, Morey, & Iverson, 2009).

Alternatively, the two selection processes triggered on dual-target trials may not be fully independent. Any competition between these processes should affect both the latencies and amplitudes of N2pc components to horizontal targets on these trials. The allocation of attention to vertical target items that appear in close temporal succession to horizontal targets may delay the attentional selection of these targets. This should be reflected by a systematic onset delay of N2pc components to H1 and H2 targets on dual-target as compared to single-target trials. Furthermore, competitive interactions between the two concurrent selection processes on dual-target trials may also result in an attenuation of N2pc amplitudes to H1 and H2 targets on these trials relative to single-target trials where no competing selection process is active.

While Experiment 1 tested whether the presence or absence of an additional vertical target has any impact on the concurrent attentional selection of horizontal targets, Experiment 2 investigated whether an onset asynchrony between two target objects is necessary to elicit independent selection processes. In previous N2pc studies (including the current Experiment 1), two colour-defined target objects always appeared in two different successively presented displays. Although the SOA between the two displays was very short (10 ms), it remains possible that selection processes for multiple target objects are triggered in parallel only when each object has a distinct onset, but not when they appear simultaneously in the same search display. In this case, strictly parallel attentional object selection processes would be specific to sequential target presentation paradigms, and may not be found in more common search tasks where multiple items with target-matching features are presented at the same time in a

single display. To test this possibility, Experiment 2 directly compared N2pc components on sequential and simultaneous presentation trials. In all trials, one horizontal and one vertical target-colour item appeared together with distractors on the opposite side. In half of all blocks, all four items appeared at the same time in a single display (simultaneous presentation trials). In the other half of blocks, the horizontal and vertical stimulus pairs were presented in two displays that were separated by a 10 ms SOA. These sequential presentation trials were identical to the dual-target trials of Experiment 1. Participants' task in Experiment 2 was to report whether the alphanumerical category (letter/digit) of the two target-colour items was the same or different. If rapid parallel attentional allocation processes to multiple target objects do not depend on the presence of an onset asynchrony between these objects, these processes should not differ between sequential and simultaneous presentation trials. In this case, the N2pc to the horizontal target-colour objects that appear simultaneously with a vertical target in the same display should be identical in terms of its amplitude and latency to the N2pc triggered by H1 targets on sequential presentation trials. Again, we calculated Bayes factors to estimate the likelihood of the null hypothesis. Alternatively, attentional selection processes may only operate in a strictly independent parallel fashion when two target objects are separated in time, but may compete when they appear simultaneously in the same display. Such competitive interactions should result in delayed and attenuated N2pc components to horizontal targets on simultaneous presentation trials relative to the N2pc to H1 targets on sequential presentation trials in Experiment 2.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Seventeen paid observers participated in Experiment 1. One was excluded due to excessive eye movements leading to a loss of more than 60% of all trials. The remaining sixteen participants were aged between 20 and 42 years (mean age 29.6 years). Nine were female, and three were left-handed. All observers had normal or corrected-to-normal vision and normal colour vision, as verified by means of the Ishihara colour vision test (Ishihara, 1972).

2.1.2. Stimuli and procedure

Stimuli were presented on a 22-in. Samsung wide SyncMaster 2233 LCD monitor at a resolution of 1280×1024 pixels with a 100 Hz refresh rate. The monitor had an 8 ms black-to-white response time, as verified with a photodiode. Participants were seated in a dimly illuminated testing booth and viewed the screen at a distance of 100 cm. Stimulus presentation, timing, and response collection were controlled by a LG Pentium PC running under Windows XP, using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.).

Stimuli were coloured uppercase letters (A, B, C, D, E, F, G, H, K, L, N, O, P, R, S, T, U, V, X, Y, or Z; $0.9^\circ \times 0.9^\circ$ of visual angle) and were presented at an eccentricity of 2.4° from central fixation against a black background. A central grey fixation point (CIE colour coordinates: 0.321/0.352; size: $0.2^\circ \times 0.2^\circ$) remained continuously present throughout each experimental block. On each trial, two consecutive stimulus displays were presented for 20 ms, and were separated by a 10 ms stimulus onset asynchrony (SOA; i.e., there was a 10 ms overlap between the two displays). The intertrial interval between the offset of the second display and the onset of the first display on the next trial was 1700 ms. Each display contained two letters. Four different letters appeared on each trial, which were selected randomly from the letter stimulus set. The four possible stimulus colours were red (0.637/0.329), green (0.264/0.556), blue (0.179/0.168), and yellow (0.423/0.461). All colours were equiluminant ($\sim$7.5 cd/m^2). Each of these colours served as target colour for four participants. The remaining three colours were used as nontarget colours. They were allocated randomly to the nontarget letters, with the restriction that repetitions of the same nontarget colour were not allowed within a trial.

Experiment 1 contained two trial conditions that were randomly intermixed in each block. In *dual-target* trials, the two consecutive stimulus displays contained each one letter in the target colour and one letter in a nontarget colour. The stimulus presentation procedures on these trials were identical to those used in our previous study (Eimer & Grubert, 2014; as illustrated in Fig. 1, top panel), except that all display items were letters. In *single-target* trials, one of the two displays contained one target-colour and one nontarget-colour letter, while the other display contained two nontarget-colour letters. The target-colour letter appeared randomly and equiprobably in either the first or second display. In each trial, one display contained a stimulus pair on the horizontal midline (to the left and right of fixation), and the other a stimulus pair on the vertical meridian (above and below fixation). In half of all trials, the horizontal stimulus display was presented first (horizontal first: H1 trials). In the other half, the vertical display preceded the horizontal display (horizontal second: H2 trials). H1 and H2 trials were randomly intermixed in each block. The display positions of the target-colour letters (left versus right, or top versus bottom) were randomly determined for each trial.

Participants' task was to report the number of target-colour letters in each trial (one versus two) by pressing the corresponding key of two custom-built vertically aligned response keys with their left or right index finger. The response-to-key and hand-to-key mappings were counterbalanced across participants. To keep participants' attention engaged during this simple enumeration task, 10% of all trials were catch trials in which one target-colour letter had a specific identity (e.g., A). Participants were instructed to refrain from responding on these trials. For each experimental block a different letter was randomly chosen from the letter set to serve as the no-go letter on catch trials. During this block, this letter was never used as nontarget letter. Catch trials were excluded from the analysis of EEG data.

Experiment 1 contained 15 blocks of 80 trials, resulting in a total of 1200 experimental trials. Each block comprised 24 dual-target trials, 48 single-target trials, and 8 catch trials. There were 3 dual-target trials for each combination of display sequence (H1 or H2), side of the horizontal target (left or right), and side of the vertical target (top or bottom), 6 single-target trials for each combination of target display (first or second) and target location (left, right, top, or bottom), and 1 catch trial for each combination of task condition (single- or dual-target), no-go letter display (first or second), and no-go letter location (horizontal or vertical). Although each block contained twice as many dual-target trials than single-target trials, the number of trials entering N2pc analyses was identical for both trial types, as half of all single-target trials contained a vertical target-colour item, and only trials with horizontally presented targets could be used to compute N2pc components. One practice block with 80 trials preceded the experiment proper.

2.1.3. EEG recording and data analyses

The continuous EEG was DC-recorded from 27 scalp electrodes (Fpz; F7, F3, Fz, F4, F8; FC5, FC6; T7, C3, Cz, C4, T8; CP5, CP6; P9, P7, P3, Pz, P4, P8, P10; PO9, PO7, PO8, PO10; Oz) with a sampling rate of 500 Hz and a digital low-pass filter of 40 Hz. No other offline filters were applied. All channels were online referenced to the left earlobe and re-referenced offline to the average of both earlobes. EEG was segmented into 500 ms epochs ranging from 100 ms prior to 400 ms after the onset of the first stimulus display.

EEG in each segment was corrected relative to the 100 ms pre-stimulus baseline, and averaged separately for each combination of trial condition (single-target, dual-target), display sequence (H1, H2), and target location (left, right). Segments contaminated with artifacts (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 1500 ms), or missing responses were excluded from EEG analyses. After trial rejection, 93.5% of all single-target trials (ranging between 75.0% and 99.4% across participants) and 92.8% of all dual-target trials (ranging between 72.5% and 98.9% across participants) that were eligible for EEG analyses (excluding catch trials and single-target trials with a vertical target) were retained.

N2pc components elicited in response to horizontal targets in the first display were quantified on the basis of mean amplitudes measured in the 180–280 ms time window after onset of the first stimulus display, ipsi- and contralateral to the horizontally presented target at lateral posterior electrodes PO7 and PO8. Mean amplitudes of N2pc components triggered in response to horizontal targets in the second display were measured in the 190–290 ms time window after onset of the first display, to account for the 10 ms SOA between the two displays. N2pc onset latencies were measured on the basis of difference waveforms obtained by subtracting ipsilateral from contralateral ERPs at PO7/8. Onset latencies were determined with a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). Sixteen grand-average difference waves were computed for each experimental condition (horizontal target in the first or second display in single- or dual-target trials), each excluding one different participant from the original sample. N2pc onset latency was defined as the point in time when each subsample's difference wave exceeded an absolute threshold value of −1.2 μV. This absolute threshold was defined as 50% of the peak amplitude of the smallest N2pc component in any of the trial conditions (the N2pc for H1 dual-target trials; see Fig. 2). *F*- and *t*-values of the statistical comparisons were corrected according to the formulas described by Ulrich and Miller (2001) and Miller et al. (1998), respectively. The corrected values are indicated with the labels 'F_c' and 't_c'. All *t*-tests were two-tailed. Effect sizes are reported in terms of Cohen's *d* (Cohen, 1988), with a confidence interval of 95%, for *t*-tests and partial eta squared (η_p^2) for *F*-tests and *t*-test on jackknifed group means (jackknifed means were fed into one-way ANOVAs to allow for error variance corrections according to the formula described by Ulrich & Miller, 2001). Therefore, for all *t*-tests on N2pc latency measures, effect sizes are reported as corrected partial eta squared (labelled η_{pc}^2; see Grubert & Eimer, 2016; for identical procedures).

Because any non-significant N2pc amplitude or latency difference between single- and dual-target trials cannot be easily interpreted in the context of conventional significance testing, we additionally calculated Bayes factors for the null-hypothesis (BF_{01}). These factors show how strongly data support the null hypothesis (as compared with the alternative hypothesis that there are differences between conditions), and correspond to the inverse of the Bayes factors for the alternative hypothesis (BF_{10}; see Rouder et al., 2009; and Wagenmakers, Lodewyckx, Kuriyal, & Grasman, 2010; for details). Reliable evidence for either hypothesis is indexed by a BF > 3 (Jeffreys, 1961), which indicates that the observed data pattern is at least 3 times more likely under this as compared to the alternative hypothesis.

2.2. Results

2.2.1. Behavioural performance

Trials with anticipatory or exceedingly slow responses (RTs faster than 200 ms or slower than 1500 ms) were removed from the analysis, resulting in the exclusion of less than 0.2% of all trials. Mean correct RTs and error rates on single- and dual-target trials were compared with two independent *t*-tests, which revealed that participants were faster, $t(15) = 11.8$, $p < 0.001$, $d = 0.83$, and more accurate, $t(15) = 4.3$, $p = 0.001$, $d > 1$, on single-target trials (mean RT: 540 ms; error rate: 0.8%) as compared to dual-target trials (596 ms; 2.6%). The percentage of False Alarms on catch trials did not differ between trials with one or two target-colour letters (6.2% versus 6.7%), $t(15) < 1$.

2.2.2. N2pc components

Fig. 2 shows ERPs elicited at posterior electrode sites PO7/8 contralateral and ipsilateral to the side of the horizontally presented target-colour item, for trials where this item appeared in the first display (H1) or in the second display (H2). These ERPs are shown separately for single-target trials (top panels) and dual-target trials (middle panels), together with N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs (bottom panel). Very similar N2pc components were elicited by H1 and H2 targets on single-target and dual-target trials, and N2pc onset latency differences matched the SOA between H1 and H2 targets on both types of trials. A repeated-measures ANOVA of N2pc mean amplitudes with the factors trial condition (single-target versus dual-target), display sequence (H1 versus H2), and laterality (electrode ipsilateral versus contralateral to the side of the horizontal target) obtained a main effect of laterality, $F(1,15) = 55.4$, $p < 0.001$, $\eta_p^2 = 0.79$, confirming that N2pc components were reliably elicited by horizontal target-colour items. Four independent follow-up *t*-tests comparing contralateral and ipsilateral ERPs in the N2pc time windows confirmed that reliable N2pc components were present to H1 and H2 targets both on single-target trials, $t(15) = 8.1$ and 6.7, both $p < 0.001$, $d = 0.56$ and 0.47, respectively, and on dual-target trials, $t(15) = 5.6$ and 7.1, both $p < 0.001$, $d = 0.49$ and 0.55, respectively.

One critical question addressed in Experiment 1 was whether N2pc components to H1 and H2 targets would be reduced in size on dual-target as compared to single-target trials. In the ANOVA, there were no interactions between laterality and display sequence, and between laterality and trial condition, both $F(1,15) < 2.2$, $p > 0.163$, indicating that N2pc amplitudes did not differ significantly between H1 and H2 targets, and between single-target and dual-target trials. However, a three-way interaction between laterality, display sequence, and trial condition approached significance, $F(1,15) = 3.6$, $p = 0.077$. As can be seen in the N2pc difference waves (Fig. 2, bottom panel), N2pc amplitudes elicited by H1 targets were numerically smaller in dual-target as compared to single-target trials, whereas no such amplitude differences were apparent for N2pc components to H2 targets. To formally test whether there was any indication for an N2pc amplitude reduction in dual-target trials, we directly compared N2pc mean amplitudes on single-target and dual-target trials, separately for H1 and H2 targets. For H1 targets, the N2pc amplitude reduction on dual-target relative to single-target trials was not statistically reliable, $t(15) = 1.383$, $p = 0.187$. The scaled JZS Bayes factor computed on the basis of this *t*-value ($BF_{01} = 2.23$) provided only moderate evidence in favour of the null hypothesis. For H2 targets, there was also no reliable N2pc difference between single-target and dual-target trials, $t(15) = 0.128$, $p = 0.900$, and the evidence in favour of the null hypothesis was very strong ($BF_{01} = 5.25$).

As predicted, N2pc components elicited by H1 targets preceded the N2pcs to H2 targets both on single-target and dual-target trials. To statistically verify this delay, N2pc onset latency estimates determined with a jackknife procedure were subjected to a repeated-measures ANOVA with the factors trial condition (single-target versus dual-target) and display sequence (H1 versus H2). The ANOVA revealed an effect of display sequence, $F_c(1,15) = 11.1$,

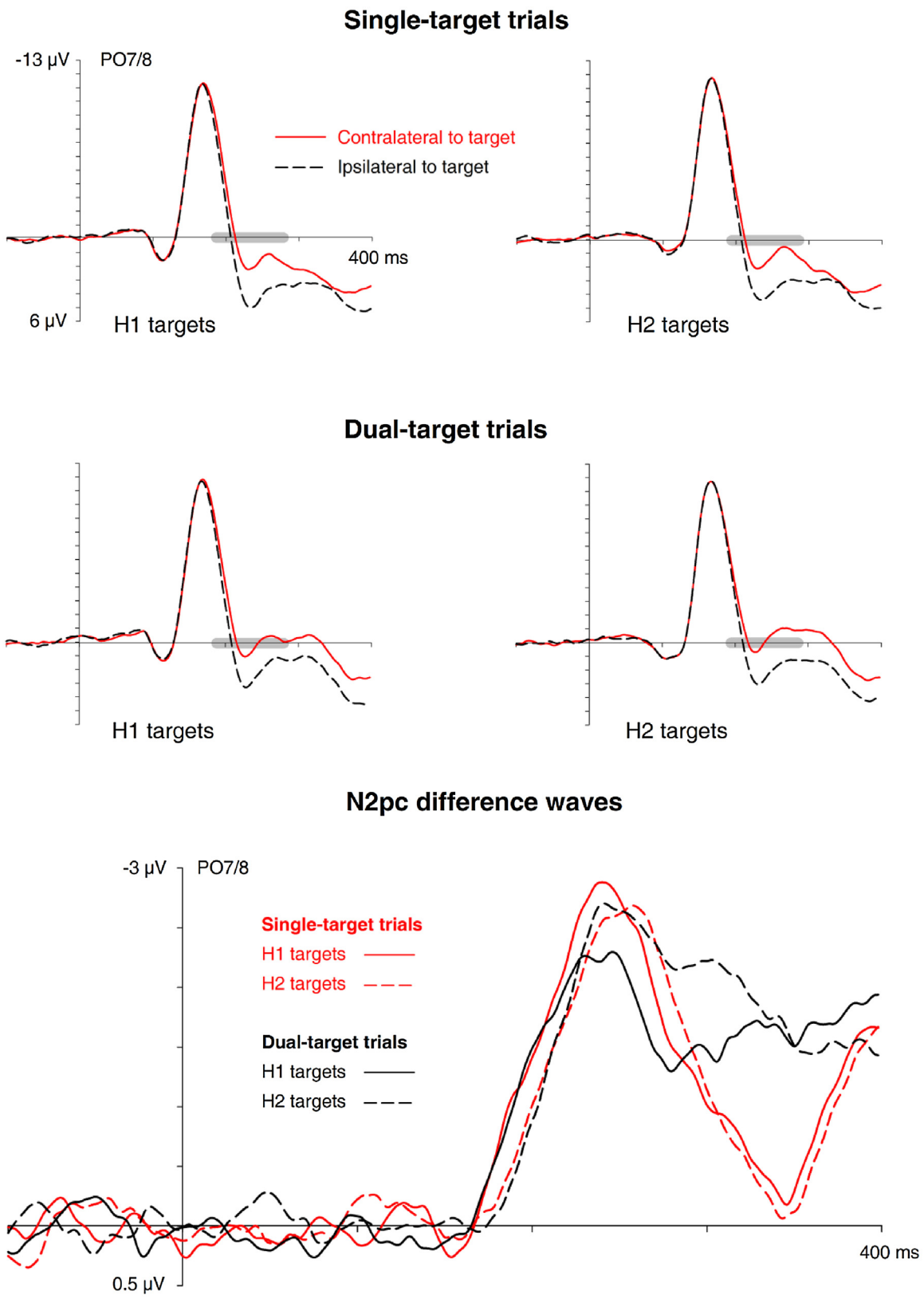

Fig. 2. N2pc results obtained in Experiment 1. Grand-average ERP waveforms measured in the 400 ms interval after the onset of the first display at posterior electrodes PO7/PO8 contralateral and ipsilateral to the target in the first display are shown separately for trials with a horizontal target in the first display (H1 targets) or in the second display (H2 targets). The top and middle panels show N2pc components obtained on single-target and dual-target trials. The bottom panel shows the corresponding N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for H1 and H2 targets on single-target and dual-target trials. The grey bars on the x-axis indicate N2pc time windows.

$p = 0.005$, $\eta^2_{pc} = 0.43$, demonstrating that the N2pc delay for H2 targets relative to H1 targets was reliable. There was no effect of trial condition, $F_c(1,15) < 1$, indicating that the onset of N2pc components to horizontal targets was entirely unaffected by the presence versus absence of an additional vertical target on the same trial. The absence of an interaction between display sequence and trial condition, $F_c(1,15) < 1$, strongly suggested that the N2pc onset delay for H2 relative to H1 targets was equally large on single-target and dual-target trials. Two separate *t*-tests showed that the N2pc delay to H2 versus H1 targets was reliably present on single-target trials (205 ms versus 194 ms), $t_c(15) = 3.0$, $p = 0.009$, $\eta^2_{pc} = 0.38$, and on dual-target trials (207 ms versus 193 ms), $t_c(15) = 2.8$, $p = 0.014$, $\eta^2_{pc} = 0.34$. The N2pc onset differences between H1 and H2 targets on single-target and dual-target trials (11 ms and 14, respectively) closely matched the objective 10 ms SOA between the two displays. Critically, these onset differences did not differ between single-target and dual-target trials, $t_c(15) = 0.609$, $p = 0.551$, providing strong evidence for the null hypothesis ($BF_{01} = 4.44$).

3. Experiment 2

3.1. Methods

3.1.1. Participants

Sixteen different observers, aged between 24 and 41 years (mean age 31.2 years), were paid to participate in Experiment 2. Eight were female, and four were left-handed. All observers had normal or corrected-to-normal vision and normal colour vision, as verified by means of the Ishihara colour vision test (Ishihara, 1972).

3.1.2. Stimuli and procedure

The stimulus parameters and procedures were essentially identical to those used in Experiment 1, with a few exceptions. Stimuli were coloured uppercase letters (T, S, B, H) or digits (1, 2, 3, 4), four of which were randomly and without replacement selected for the four stimulus locations in each trial. The *sequential presentation* condition was similar to the dual-target condition of Experiment 1. Two displays with a target-colour item and a distractor item in a different nontarget colour were presented consecutively. The two displays were presented for 20 ms each and were separated by a 10 ms SOA, as in Experiment 1 (Fig. 1, top panel). The ISI between the offset of the second display and the onset of the first display in the next trial was 1970 ms (2000 ms – 30 ms presentation time in total). Each trial included one display with a horizontal target-nontarget pair and one display with vertical stimulus pair, and the order in which these two displays appeared (horizontal first versus second, H1 versus H2 trials) varied randomly across trials. In the new *simultaneous presentation* condition that was presented in separate blocks, the two targets were presented together with two nontarget-colour items within a single stimulus display. This search array was presented for 20 ms and was followed by a 1980 ms ISI (2000 ms – 20 ms presentation time) before the onset of the stimulus display in the next trial. The two presentation conditions were delivered in separate blocks. Participants' task was to report whether the two target-colour items in each trial were the same (both digits or letters) or whether they were different (one letter and one digit) by pressing one out of the two response keys. Same and different response trials were equiprobable and presented intermixed in each experimental block. The response-to-key and hand-to-key mappings were counterbalanced across participants, but remained the same for each participant in the two blocked presentation conditions. In contrast to Experiment 1, no catch trials were included in Experiment 2.

The sequential presentation condition was tested in 6 consecutive blocks of 64 trials. Each block comprised 8 trials for each combination of display sequence (H1 or H2), side of horizontal target (left or right), and location of vertical target (top or bottom). The simultaneous presentation condition was tested in 3 successive blocks of 64 trials, and each block contained 16 trials for each of the four possible combinations of target locations (left and top, left and bottom, right and top, right and bottom). This resulted in a total of 576 experimental trials in Experiment 2. The order of presentation conditions was counterbalanced between participants so that eight participants completed the sequential before the simultaneous presentation condition and vice versa for the other eight participants. There were twice as many blocks in the sequential presentation condition, because separate N2pc components had to be measured for H1 and H2 targets on different trials. In the simultaneous presentation, only a single N2pc was measured to target-colour objects on the horizontal midline. As a result, the same number of trials was available for computing the two N2pc components in the sequential presentation condition and the single N2pc in the simultaneous presentation condition. Each participant completed a practice block of 64 trials prior to the start of the first experimental block.

3.1.3. EEG recording and data analyses

Those were essentially identical to Experiment 1 with the following exceptions. EEG was averaged separately for each combination of presentation condition (sequential, simultaneous) and horizontal target location (left, right). For the sequential presentation condition, separate averages were computed for trials with H1 and H2 targets. After trial exclusion due to artefacts, and fast, slow, incorrect or missing responses, the percentage of trials retained for EEG analysis was 93.4% in the sequential presentation condition (ranging between 78.4% and 98.7% across participants), and 93.7% in the simultaneous presentation condition (ranging between 83.3% and 96.9% across participants). Mean amplitudes of N2pc components triggered in response to H1 targets in the sequential presentation condition and to horizontal targets in the single display in the simultaneous presentation condition were measured in the 180–280 ms time window after onset of these displays, ipsi- and contralateral to the horizontally presented target at lateral posterior electrodes PO7 and PO8. Mean amplitudes to H2 targets in the sequential presentation condition were quantified in the 190–290 ms time window after onset of the first display (accounting for the 10 ms SOA between the two displays). N2pc onset latencies were measured at −0.7 μV (50% of the peak amplitude of the smallest N2pc component, the N2pc to H1 targets in the sequential presentation condition; see Fig. 3).

3.2. Results

3.2.1. Behavioural performance

Less than 0.3% of all trials were removed due to anticipatory or exceedingly slow responses (RTs faster than 200 ms or slower than 1500 ms). Independent *t*-test revealed no differences between sequential and simultaneous presentation conditions for mean correct RTs (618 ms versus 627 ms), $t(15) = 1.7$, $p = 0.107$, or error rates (both 2.9%), $t(15) < 1$.

3.2.2. N2pc components

The top panels of Fig. 3 show ERPs elicited at posterior electrode sites PO7/8 contralateral and ipsilateral to the side of the horizontally presented target-colour item. ERPs are shown separately for H1 and H2 targets in the sequential presentation condition (left and middle panel), and for horizontal targets in the simultaneous presentation condition that were accompanied by a vertical target in the same display (right panel), together with the corresponding N2pc difference waveforms (bottom panel). Similar N2pc components were elicited by all three types of targets. The N2pc

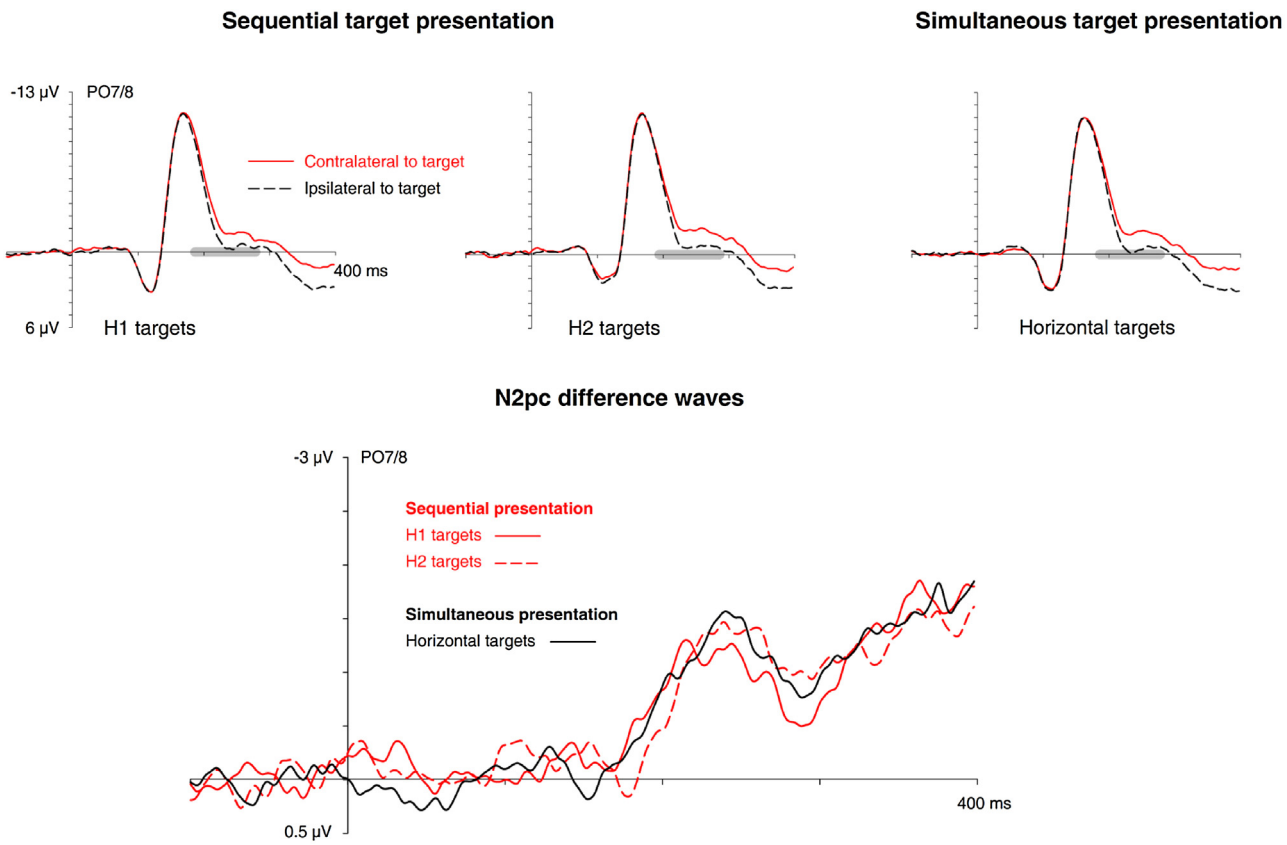

Fig. 3. N2pc results obtained in Experiment 2. Grand-average ERP waveforms measured in the 400 ms interval after the onset of the first display at posterior electrodes PO7/PO8 contralateral and ipsilateral to the target in the first display are shown separately for trials with H1 and H2 targets in the sequential presentation condition, and for horizontal targets in the simultaneous presentation condition. The bottom panel shows the corresponding N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for these three types of horizontal targets. The grey bars on the x-axis indicate N2pc time windows.

to horizontal targets in the simultaneous presentation condition emerged at exactly the same time as the N2pc to H1 targets in the sequential presentation condition, and the N2pc onset delay to H2 targets in this condition again matched the SOA between the two displays.

A repeated-measures ANOVA on N2pc mean amplitudes with the factors task condition (H1 target, H2 target, horizontal target in the simultaneous presentation condition) and laterality (electrode ipsilateral versus contralateral to the side of the horizontal target) obtained a main effect of laterality, $F(1,15) = 35.2$, $p < 0.001$, $\eta_p^2 = 0.70$, but no interaction between task condition and laterality, $F(2,30) < 1$, demonstrating that N2pc components to horizontal targets in the sequential and simultaneous presentation conditions did not differ in amplitude. Subsequent *t*-tests comparing contralateral and ipsilateral ERPs in the N2pc time windows confirmed the presence of reliable N2pc components to H1 and H2 targets in the sequential presentation condition and horizontal targets in the simultaneous presentation condition, $t(15) = 6.1$, 5.9, and 5.0, respectively, all $p < 0.001$, $d = 0.24$, 0.23, and 0.22, respectively. To formally test for any N2pc size differences between trials with H1 targets in the sequential presentation condition and with horizontal targets in the simultaneous presentation condition, N2pc mean amplitudes on these two types of trials were directly compared. There was no reliable difference, $t(15) = 0.696$, $p = 0.497$, and strong evidence in favour of the null hypothesis ($BF_{01} = 4.21$).

As can be seen in the N2pc difference waves (Fig. 3, bottom panel), the N2pc to H2 targets was delayed relative to the N2pc to H1 targets in the sequential presentation condition, as in Experiment 1. A jackknife-based analysis confirmed that this onset delay was reliable (207 ms versus 193 ms), $t_c(15) = 2.6$, $p = 0.022$, $\eta_{pc}^2 = 0.30$, and mirrored the objective SOA between the two displays. The N2pc to H2 targets also emerged reliably later than the N2pc to horizontal targets in the simultaneous presentation condition (195 ms), $t_c(15) = 2.5$, $p = 0.023$, $\eta_{pc}^2 = 0.30$. Importantly, there was no N2pc onset difference between H1 targets and horizontal targets in the simultaneous presentation condition, $t_c(15) = 0.276$, $p = 0.786$, providing strong evidence for the null hypothesis that N2pc components to horizontal targets were triggered at the same time regardless of whether or not a second vertical target item was present in the same display ($BF_{01} = 5.11$).

4. Discussion

Previous ERP studies have measured N2pc components as a marker of attentional target selection in tasks where two target/nontarget stimulus displays were presented in rapid succession, and found evidence for the rapid allocation of spatial attention to both target objects (Eimer & Grubert, 2014; Grubert & Eimer, 2015; Jenkins et al., in press). These observations show that multiple attentional selection processes can be activated concurrently, but do not provide clear-cut evidence that these processes operate in a genuinely parallel and independent fashion. To qualify as a parallel process, the allocation of attention to a particular target has to be shown to be unaffected by whether or when an additional selection process is elicited simultaneously for another target object. The current study has provided this evidence. In Experiment 1, the attentional selection of colour-defined target objects, as reflected by the onset latencies and amplitudes of N2pc components triggered by this target, was not modulated by the presence versus absence of the concurrent selection of another target that was

presented in close temporal proximity. Experiment 2 showed that two targets can be selected in parallel regardless of whether they appear sequentially in two successive displays or simultaneously in the same search display.

Both experiments included trials where two colour-defined targets appeared on the horizontal or vertical midline in two successive displays that were separated by a 10 ms SOA (dual-target sequential presentation trials; see Fig. 1). Confirming previous findings (e.g., Eimer & Grubert, 2014), the N2pc to horizontal target objects in the first display (H1 targets) preceded the N2pc to such targets in the second display (H2 targets) by 10–15 ms. This N2pc onset latency difference was significant in both experiments, and closely matched the objective SOA between the two displays, demonstrating that the attentional selection of H1 and H2 targets followed their own independent time course. Importantly, the N2pc components to H1 and H2 targets overlapped in time and did not differ in amplitude, which is consistent with the hypothesis that they reflect parallel selection processes where attention is allocated independently and concurrently to both target objects. It is important to note that each display contained two equally salient objects in two different colours, and that the target object in each display could only be found on the basis of its colour. For this reason, target selection had to be controlled by a colour-specific search template, and could not be guided by bottom-up salience driven processes (feature pop-out; e.g. Treisman & Gelade, 1980).

In Experiment 1, N2pc components to H1 and H2 targets on dual-target trials were compared to the corresponding N2pcs elicited on single-target trials where the other display did not contain a vertical target object, in order to determine whether the allocation of attention to horizontal target objects was genuinely independent from the concurrent attentional selection of the target object in the other display. As can be seen in Fig. 2, N2pc onset latencies were virtually identical on single-target and dual-target trials, both for H1 targets (194 ms and 193 ms post-stimulus respectively), and H2 targets (205 ms and 207 ms). The N2pc onset difference between H1 and H2 targets did not differ between single-target and dual-target trials, and the corresponding Bayes factor supported this conclusion. This provides strong evidence that the speed with which attention was allocated to a target object in the first or second display was completely unaffected by whether or not an additional attentional selection process was activated in response to a vertical target object in the immediately preceding or subsequent display. There were also no reliable N2pc amplitude differences between single-target and dual-target trials for either H1 or H2 targets. For H2 targets, the evidence for the absence of any such amplitude differences was very strong, whereas there was a small non-significant tendency towards larger N2pc amplitudes to H1 targets on single-target trials. Overall, these findings suggest that there were no competitive interactions between the rapid allocation of attention to horizontal target objects and the concurrent attentional selection of vertical targets. The fact that N2pc onset latencies and amplitudes to horizontal target objects in Experiment 1 remained essentially unaffected by the presence or absence of a vertical target on the same trial provides strong evidence that these two attentional selection processes operate independently, in line with the predictions of strictly parallel models.

Further evidence for this conclusion was provided by Experiment 2, where the attentional selection of horizontal target objects was compared between simultaneous presentation trials where these targets appeared at the same time as vertical targets, and sequential presentation trials, where the two target objects appeared in different displays that were separated by a 10 ms SOA. The N2pc to horizontal targets on simultaneous presentation trials emerged at almost exactly the same time as the N2pc to H1 targets on sequential presentation trials (195 ms versus 193 ms post-stimulus; see Fig. 3), and there was no amplitude difference between these two N2pc components. These observations, which were confirmed by the corresponding Bayes factors, strongly suggest that the allocation of attention to a horizontal target object was not selectively impaired by the simultaneous presence of a vertical target in the same display, as compared to trials where these two target objects were presented in successive displays. They show that the presence of concurrent parallel attentional target selection processes is not specific to situations were individual target objects have a distinct onset, but are also elicited in response to objects that appear simultaneously in the same search display.

It should also be noted that a very similar temporal pattern of N2pc components to H1 and H2 targets was found in Experiment 1, where participants simply reported the number of target items on each trial (one versus two), and in Experiment 2, where they had to match their alphanumerical category. This similarity suggests that the presence of rapid parallel attentional selection processes does not critically depend on the level of target processing imposed by particular task instructions. Such processes are not only activated when multiple colour-defined target objects have to be identified (as in Experiment 2), but also in tasks where participants only have to detect their presence (as in Experiment 1).

As can be seen in Fig. 2 (bottom panel), Experiment 1 revealed a marked difference between the lateralised ERP waveforms elicited on single-target as compared to dual-target trials. This difference was present during the 300–400 ms post-stimulus time window that followed the N2pc component. On single-target trials, difference waveforms returned to baseline, before a second contralateral negativity started to emerge. This later effect marks the onset of the sustained posterior contralateral negativity (SPCN component) that typically follows the N2pc and is assumed to reflect the attentional activation of target representations in visual working memory (e.g., Mazza, Turatto, Umilta, & Eimer, 2007; see also Eimer, 2014; for further discussion). On dual-target trials, the contralateral negativity during the N2pc time window did not return to baseline at around 350 ms post-stimulus, but remained present in a sustained fashion during the post-N2pc time interval.[1] The presence of these longer-latency ERP lateralisation differences between single-target and dual-target trials was a new and unexpected finding, and the reason for these differences is as yet unclear. One possibility is that a perceptual attentional focus on a horizontal target-colour object on the left or right side dissipates rapidly when only one target selection process is active, but is maintained for a longer period when a second colour-based attentional selection process is simultaneously activated at a different location. This and other possible interpretations of this apparent difference in the temporal extension of early posterior ERP lateralisations during single- and multiple-target selection episodes will have to be investigated more systematically in future research.

In summary, the current N2pc study has demonstrated that attentional target selection processes that are elicited within the first 200 ms after stimulus onset are unaffected by whether or when another selection process is activated, in line with the hypothesis that these processes operate in a strictly parallel independent fashion. It is important to note that the N2pc reflects a relatively early sensory-perceptual stage of attentional object selection where objects with target-defining features trigger spatially selective modulations of visual activation. The parallel attentional processing of multiple target objects at this early stage does of course not rule out the possibility that mechanisms of attentional selectivity at

[1] An analysis of ERP mean amplitudes measured during the 300–400 ms post-stimulus interval obtained a significant interaction between laterality and trial condition (single-target versus dual-target), $F(1,15) = 16.3$, $p = 0.001$, $\eta_p^2 = 0.52$, demonstrating that the difference in ERP lateralisation between these two types of trials during this time interval was reliable.

subsequent processing stages where selected objects are encoded into working memory and are eventually recognised no longer operate in a fully parallel fashion, but also involve competitive and perhaps even strictly serial mechanisms.

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