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Attentional capture in visual search: capture and post-capture dynamics revealed by EEG

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Abstract

Sometimes, salient-but-irrelevant objects (distractors) presented concurrently with a search target cannot be ignored and attention is involuntarily allocated towards the distractor first. Several studies have provided electrophysiological evidence for involuntary misallocations of attention towards a distractor, but much less is known about the mechanisms that are needed to overcome a misallocation and re-allocate attention towards the concurrently presented target. In our study, electrophysiological markers of attentional mechanisms indicate that (i) the distractor captures attention before the target is attended, (ii) a misallocation of attention is terminated actively (instead of attention fading passively), and (iii) the misallocation of attention towards a distractor delays the attention allocation towards the target (rather than just delaying some post-attentive process involved in response selection). This provides the most complete demonstration, to date, of the chain of attentional mechanisms that are evoked when attention is misguided and recovers from capture within a search display.

Keywords: attention, distraction, ERP-component latency, event-related potentials (ERPs), posterior contralateral negativity (PCN)

1 Introduction

When searching for a specific object in a crowded scene, other salient objects (*distractors*) are often present in addition to the search target. Recent studies have shown that a suppression mechanism can prevent attention allocations to such distractors (Gaspar & McDonald, 2014; Gaspar, Christie, Prime, Jolicoeur, & McDonald, 2016; Hickey, Di Lollo, & McDonald, 2009; Jannati, Gaspar, and McDonald, 2013; Sawaki, Geng, & Luck, 2012). Sometimes, however, this mechanism fails and a distractor is attended (Burra & Kerzel, 2013; Gaspar et al., 2016; Hickey, McDonald, & Theeuwes, 2006; Kiss, Grubert, Petersen, & Eimer, 2012). Theories of visual search assume that the order of attention allocations is guided by a pre-attentive spatial representation of the visual world (*priority map*; Bisley & Goldberg, 2010; Itti & Koch, 2001; Li, 1999, 2002; Wolfe, 1997, 2007). Values on this map are determined based on both (bottom-up) stimulus features and (top-down) task goals. A distractor captures attention if it achieves a higher value on the priority map than the target. Despite having a lower (initial) value on the priority map, the target is eventually attended and a correct response is issued. But how do observers get there? Although there is abundant evidence for interference induced by a salient distractor (e.g., Theeuwes, 1991, 1992; Zehetleitner, Koch, Goschy, & Müller, 2013) and that a salient distractor is sometimes attended involuntarily (Burra & Kerzel, 2013; Fukuda & Vogel, 2009, 2011; Gaspar et al., 2016; Hickey et al., 2006; Kiss et al., 2012, Lien, Ruthruff, Goodin, & Remington, 2008), little is known about the exact attentional mechanisms involved in the recovery from a misallocation of attention. In the present study, we aimed to break down the processes that are involved when, after having been misguided, attention is disengaged from the distractor and reallocated towards the concurrently presented target.

After a misallocation, attention might simply move on to the next object on the priority map (Schwarz & Miller, 2016; Wolfe, 1997). That is, termination of a misallocation might be effortless. Alternatively, the distractor must be actively suppressed (i.e., attention has to be released) before the next object on the priority map can be attended. In line with the latter possibility, evidence exists that *voluntary* allocation of attention towards a *target* is terminated by an active suppression mechanism (Sawaki et al., 2012; Toffanin, de Jong, & Johnson, 2011), perhaps to ensure that attention is returned to a neutral position (e.g., fixation) in readiness for the next search trial. Such a suppression mechanism might also terminate the processing of a *distractor* after it was *involuntarily* attended, permitting attention to proceed to the next object on the priority map.

Eventually after capture, attention must be reallocated towards the target. Active suppression of the distractor should therefore go along with a shift of attention from the distractor to the target. This has two implications for the temporal dynamics of target processing: first, the target should be attended after the distractor was attended (rather than before or in parallel with the distractor); and, second, attention allocation towards the target (rather than just some post-attentive process, such as response selection) should be delayed when a distractor is present, compared to when the target is the only singleton in the display. These dynamics are of theoretical importance, because sequential allocations of attention would be predicted by theories that assume search to be strictly serial, with only one item being focally attended at a time (e.g., Moran, Zehetleitner, Müller, & Usher, 2013; Liesefeld, Moran, Usher, Müller, & Zehetleitner, 2016; Schwarz & Miller, 2016; Wolfe, 1997).

To sum up, we predict a very specific sequence of attentional mechanisms when attention is first misallocated to a distractor and then needs to be redirected to the target: (i) attention allocation towards the distractor, (ii) active suppression of the distractor, and (iii) attention shift towards the target.[1]

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[1] Sawaki and Luck (2013) reported such a sequence in a paradigm in which two displays were presented in succession: a task-irrelevant ‘cue’ display presented for 100 ms, which consisted of four (heterogeneously) colored circles, one of them in the target color (i.e., the distractor), followed, at a stimulus onset asynchrony of 300 ms, by the ‘search’ display containing the color-defined target. However, in this design, the distractor shares the (exact) target feature and can occur at the subsequent

To demonstrate the predicted sequence, direct tracking of these hypothesized attentional mechanisms over time is required. One relevant measure, depicting the dynamics of spatial attention, is the *N2pc* component (also referred to as PCN; e.g., Töllner, Gramann, Müller, Kiss, & Eimer, 2008; Töllner, Conci, & Müller, 2015) of the event-related potential (ERP) waveform: a transient negative increase in activity over posterior electrode sites (typically PO7/8) contralateral to the attended object (e.g., Luck & Hillyard, 1994; Eimer, 1996; Woodman & Luck, 1999, 2003; Töllner, Müller, & Zehetleitner, 2012). Woodman and Luck (1999, 2003) showed that successive shifts of attention in a search array with two targets, one on each side of the display, can elicit a very telling ERP pattern: first an N2pc to the first target followed by one to the second target. This pattern of two consecutive N2pc components of opposite polarity is often referred to as 'N2pc flip' (e.g., Jannati et al., 2013; McDonald, Green, Jannati, & Di Lollo, 2013). Another relevant measure is the P_D (distractor positivity) component: a positive increase in activity contralateral to the distractor over the same posterior electrode sites, which is taken to reflect an active suppression mechanism (Gaspar & McDonald, 2014; Hickey et al. 2009; Jannati et al., 2013; Sawaki et al. 2012; Toffanin et al. 2011).

Accordingly, we expect a very specific sequence of ERP components mirroring the predicted sequence of attentional mechanisms: (i) attentional capture would be reflected by a distractor N2pc; (ii) suppression of the distractor would be reflected by a subsequent distractor P_D; and (iii) the shift of attention to the target would eventually be reflected by a

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target location (the cue, although spatially non-predictive, is not counter-predictive as to the target location), and because it is presented earlier, it does not directly compete with the target for attentional selection. Arguably, therefore, this design has limited potential for understanding the temporal dynamics of attentional selection when both are defined by separable features and occur consistently at different locations within the same, search display. In line with this, such a sequence has never been coherently (and reliably) demonstrated in any study with concurrent presentation of target and distractor (see Discussion for further details).

target N2pc that follows the distractor N2pc (N2pc flip). To date, there is, to our knowledge, no single study that has demonstrated this complete sequence with the expected timing within the same search display!

2 Materials and Methods

Positively demonstrating such a sequence requires an experimental situation in which target and distractor are presented in the same display, so that they compete for attention, and the distractor is reliably the first item selected. To realize this, first of all, the distractor must be more salient than the target. Saliency is a direct function of the feature contrast, for instance in terms of orientation, between a given stimulus and the items in its nearer surround (e.g., Nothdurft, 1993; Li, 1999). Thus, one way to achieve tight control over saliency involves presenting, for example, tilted target and distractor bars within a dense, rather than a sparse, array of vertical (non-target) bars (Rangelov, Müller, & Zehetleitner, 2013, 2017; Liesefeld, Moran, Usher, Müller, & Zehetleitner, 2016). In such arrays, saliency directly depends on the degree of tilt relative to the non-targets, and the distractor would be rendered more salient than the target by being tilted more strongly.

Second, even a highly salient distractor can often be successfully suppressed (Gaspar & McDonald, 2014; Gaspar et al., 2016; Hickey et al., 2009; Jannati et al., 2013). Suppression might be possible when cognitive (top-down) control mechanisms are able to attenuate distractor feature signals and/or boost target signals so that even a distractor physically more salient than the target would receive a lower (effective ‘selection saliency’) value on the priority map (Zehetleitner et al., 2013). Thus, selective weighting of target and distractor feature signals would have to be rendered ineffective to ensure that the distractor is reliably attended. Arguably, this can be achieved by defining both target and distractor as orientation singletons (i.e., to use an intra-dimension distractor; see Müller, Geyer, Zehetleitner, &

Krummenacher, 2009; Müller, Reimann, & Krummenacher, 2003; Zehetleitner, Goschy, & Müller, 2012).

2.1 Participants

Sixteen participants (mean age = 27 years, range = 21-35 years, 9 women, all right-handed), recruited at Ludwig-Maximilians-Universität München, were paid for their participation or received course credit. All reported normal or corrected-to-normal vision and gave written informed consent. This sample size is sufficient to detect effects of size $d_z = 0.65$ and above with a probability of $1-\beta = .8$ ($\alpha = .05$, one-tailed).

2.2 Stimuli

Stimuli were white bars (0.16 × 0.80°) presented on a CRT monitor, at a viewing distance of approximately 100 cm, against a dark gray background. Search displays (Fig. 1) consisted of 60 bars arranged around four concentric rings (with radii of 1.1°, 2.2°, 3.3°, and 4.4°) centered on a central white fixation cross (0.48°). Each bar contained a hole (0.03° in height) in its upper or lower part. The target was tilted by 12° and the distractor by 45°.

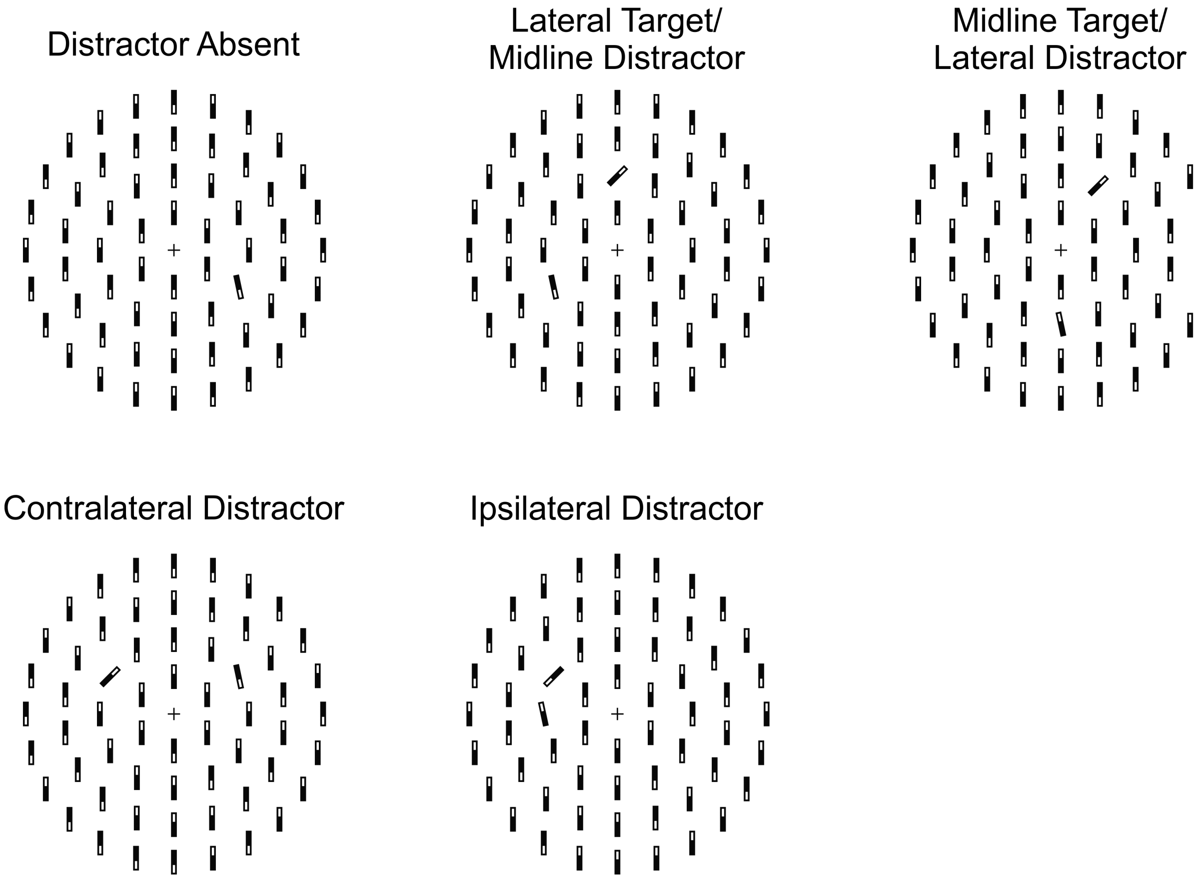

Figure 1. Schematic sample displays from each condition in the left-tilted-target group. Actual displays contained white bars on a dark gray background.

The target bar and the singleton distractor bar were consistently tilted in opposite directions (tilt direction counterbalanced between participants), so that the distractor clearly did not match the target description. As concerns the latter, note that tilt direction has been shown to be a basic, *categorical feature* capable of guiding search (Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992; Wolfe 2007).

We employed the five types of displays as illustrated in Figure 1. Because N2pc and P_D are relative increases in activity contralateral to an attended/suppressed object, these can only be observed with lateralized stimuli. Distractor-absent displays provide a baseline to examine the target N2pc when the (lateralized) target is the only singleton in the display. This is compared to displays with lateralized targets in which a distractor is presented on the midline (*lateral-target/midline-distractor* condition); such a distractor can hamper search, while not eliciting lateralized attention-related components (N2pc/P_D). To examine for these potential distractor-related components, the target is presented on the midline and the distractor is lateralized in the *midline-target/lateral-distractor* condition. In the *contralateral-distractor* condition, target and distractor are presented on opposite sides of the display, so that the target and distractor N2pcs would be of opposite polarity and the target N2pc and distractor P_D of the same polarity. Finally, in the *ipsilateral-distractor* condition, target and distractor are on the same side of the display, so that the respective N2pcs would be of the same polarity, whereas the distractor P_D would be of the opposite polarity.

2.3 Design and Procedure

On each trial, the search array was presented for 1,500 ms (see Woodman & Luck, 1999, and Johnson, Woodman, Braun, & Luck, 2007, for comparable presentation times). Participants' task was to indicate the position of the 'hole' (upper/lower part) in the target bar by pressing the designated key on a computer mouse with their left or right thumb (key-to-response assignment counterbalanced). The response had to be given within 4,000 ms after the onset of the search display. In case of an incorrect or delayed response, the fixation cross changed color for 1,000 ms, turning red if the answer was wrong and blue if it was too slow. The inter-trial interval was jittered between 800 and 1,600 ms. Participants were instructed to maintain eye fixation on a central cross that remained present throughout each block. They were informed that the target and the additional singleton distractor were always located on the second ring (2.2° eccentricity). Training consisted of 48 (unanalyzed) trials. Then, participants performed 29 blocks of 48 trials each (1,392 trials in total), that is: 232 trials per distractor-present condition (contralateral distractor, ipsilateral distractor, lateral target/midline distractor, midline target/lateral distractor) and 464 distractor-absent trials. After each block, participants received feedback on their mean response accuracy.

2.4 Electrophysiological recording and analysis

The electroencephalogram (EEG) was recorded continuously via 58 Ag/AgCl electrodes positioned according to the international 10-10 system. A left-mastoid reference was used during recording, and signals were re-referenced offline to the average of both mastoids. Vertical and horizontal ocular artifacts were monitored via four additional electrodes above and below the left eye and at the outer canthi of both eyes. All impedances were kept below 10 kΩ. Signals were amplified (250-Hz low-pass filter, 10-s time constant; BrainAmp DC, BrainProducts, Munich, Germany) and sampled at 1,000 Hz. EEG data were processed with custom-written Matlab (The Mathworks, Natick, MA) code using functions from EEGLAB (Delorme & Makeig, 2004) and Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011). We applied 0.5-Hz high-pass and 40-Hz low-pass FIR filters (EEGLAB default), ran an independent component analysis (ICA; EEGLAB, extended mode) and removed ICA components representing blinks or horizontal eye movements. After these preprocessing steps on the continuous EEG, data were segmented into epochs from -200 ms to 700 ms relative to search display onset and baseline-corrected with respect to the pre-stimulus interval. Trials with artifacts in the analyzed channels (PO7/8; voltage steps larger than 50 µV per sampling point, activity changes less than 0.5 µV within a 500-ms time window, or absolute amplitude exceeding ±60 µV), horizontal eye movements (detected prior to the ICA), or incorrect responses were excluded (6.2% overall).

To extract ERPs, EEG epochs from each condition were averaged separately for contralateral and ipsilateral electrodes (relative to the distractor in the midline-target/lateral-distractor condition and relative to the target in all other conditions), and the resulting individual ipsilateral ERPs were subtracted from the contralateral ERPs. Lateralized components were analyzed in these difference waves at electrode sites PO7/8. For component latency estimation, we used 50%-area latency (Luck, 2005, pp. 239-242), where component area was defined as the region bounded by the ERP, a threshold set at 30% of the component's amplitude, and the two time points where the ERP crossed the threshold (on- and offset of the respective component). The search for on- and offsets started at the highest local peak within the search interval and proceeded towards both search intervals. If no on- or offset was found, the respective search interval border served as the boundary instead. The pattern of results (including all decisions on statistical significance) was the same with 30%-amplitude latency (component onset). We report area latency, because it is more representative for the distribution of latencies. Whereas onset latency is biased towards the earliest component onsets, area latency reflects the median latency of a component.

To determine analysis windows for amplitudes of the components of interest, we performed 50%-area latency detection on the strongest component of the respective polarity in the respective grand-average difference wave and defined amplitudes as the mean activity in a 30-ms window centered on these time points. For statistical tests on differences in component latencies, these latencies were determined for each participant within a common time window encompassing on- and offsets of all analyzed components (143–444 ms). As we had strong a-priori hypotheses about the direction of effects (e.g., we predicted that a lateralized target would elicit a *negative* component [the target N2pc] in the difference wave and that the target N2pc would be *delayed* on distractor-present trials), t-tests were performed one-tailed, except for tests predicted to be non-significant (as indicated).

3 Results

3.1 Behavior

Correct responses were slower (1,016 vs. 791 ms, $t(15) = 13.32$, $p < .001$, $d_z = 3.33$) and error rates higher (6.6% vs. 3.0%, $t(15) = 3.58$, $p = .001$, $d_z = 0.89$) when a distractor was present. Additionally, there was a strong effect of target-distractor distance (one-way repeated-measures analyses of variance with 6 levels, distance 1 [direct neighbors, 1,076 ms] to distance 6 [five intervening objects, 1,001 ms], pooled across all distractor-present conditions) on RTs, $F(5,75) = 12.51$, $p < .001$, $\eta^2_p = .45$, and error rates, $F(5,75) = 3.45$, $p = .007$, $\eta^2_p = .19$. This type of effect has been taken as behavioral indication that the distractor effect is due to spatial-attentional processes, rather than generally slowed processing in the presence of a distractor (non-spatial 'filtering costs'; Hickey & Theeuwes, 2011; Gaspar & McDonald, 2014). Notwithstanding these distance effects, we observed costs for each distractor distance for RTs (all > 184 ms), all ts > 8.80, all ps < .001, all d_zs > 2.2, and error rates (all > 1.9%), all ts > 2.12, all ps < .026, all d_zs > 0.53.

3.2 Event-related potentials

3.2.1 The distractor is first attended and then suppressed

First, we tested whether the distractor captured attention. Indeed, a prominent distractor N2pc emerged in the midline-target/lateral-distractor condition (-1.06 µV; Fig. 2 *C*), $t(15) = 4.55$, $p < .001$, $d = 1.14$. Having established that the distractor was attended, we went on to ask whether it must be actively suppressed to release attention, or whether attention would simply automatically move on to the next most salient object. In line with the former alternative, a prominent distractor P_D emerged on midline-target/lateral-distractor trials (1.33 µV), $t(15) = 4.90$, $p < .001$, $d = 1.23$, and, importantly, it manifested clearly later (113 ms) than the distractor N2pc, $t(15) = 6.56$, $p < .001$, $d_z = 1.64$.

3.2.2 Distractor presence delays attention towards the target.

In the distractor-absent condition, the lateral target elicited a pronounced N2pc (-0.87 µV), $t(15) = 4.43$, $p < .001$, $d = 1.11$, indicating that spatial attention was directed to the target (Fig. 2 *A*). Such a target N2pc also emerged on lateral-target/midline-distractor trials (-0.60 µV; Fig. 2 *B*), $t(15) = 3.54$, $p = .001$, $d = 0.89$, though 59 ms later, on average. This latency difference was significant, $t(15) = 4.15$, $p < .001$, $d_z = 1.04$, indicating that the presence of a distractor delayed the allocation of attention to the target.

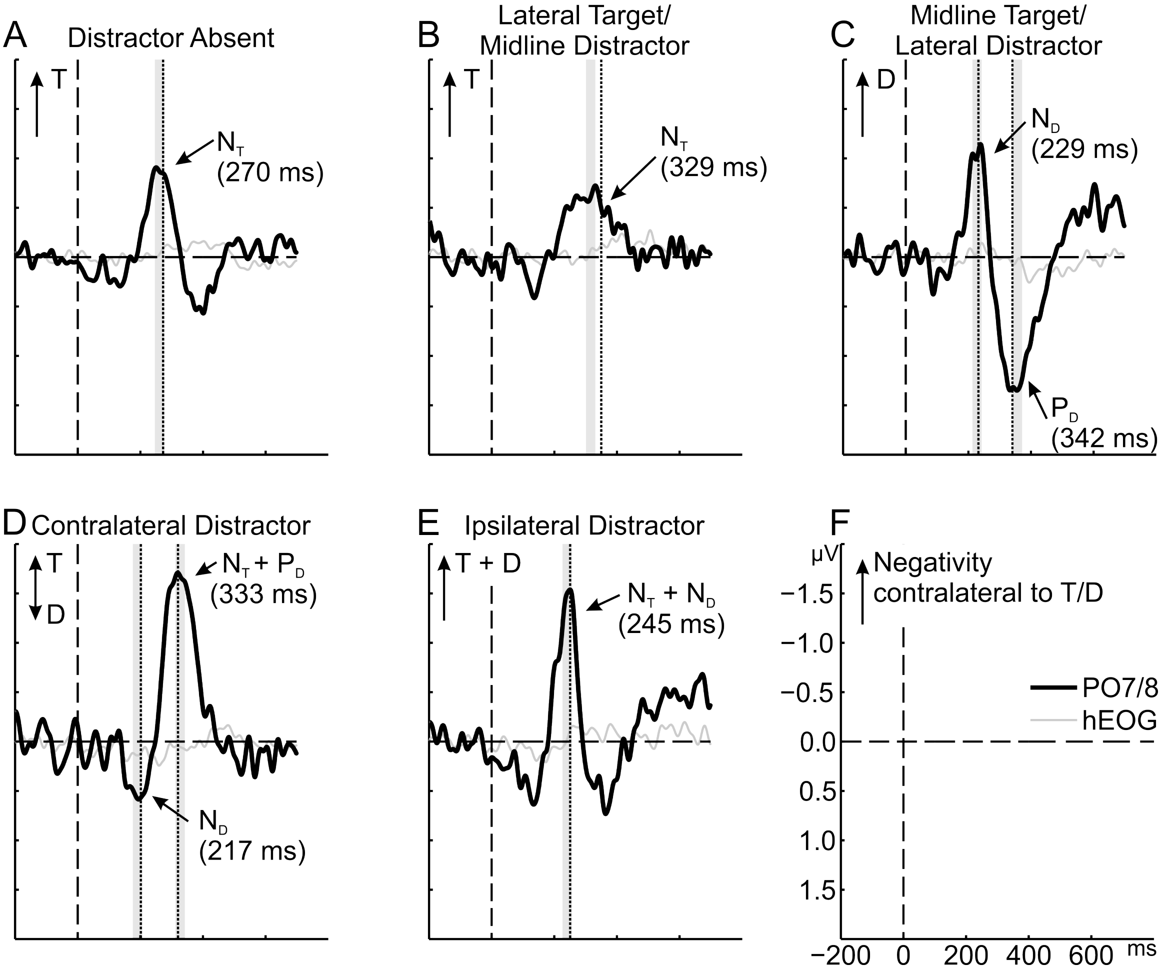

Figure 2. Difference waves at PO7/8 for the five conditions (*A*-*E*) and the scale (*F*; negative is up). Shadings indicate the mean-amplitude windows for the respective N2pc/P_D components. Analyzed components are labeled with N = negativity (N2pc) and P = positivity and subscripts T = target and D = distractor. Arrows in the upper left of each panel indicate the position of the singletons (T and/or D). Negativities in the arrow direction indicate attention allocation towards the respective singleton location. The dotted vertical lines indicate mean component latencies (numerical latencies are given in parentheses below the respective component labels). To corroborate that the observed components were not due to saccadic activity, the residual horizontal-EOG difference waves are plotted in addition.

3.2.3 An attention shift from the distractor to the target.

We predicted that in distractor-present displays, attention would be allocated first to the (more salient) distractor and only afterwards to the (less salient) target. To examine whether the distractor was indeed attended before the target, we compared the latency of the distractor N2pc in the midline-target/lateral-distractor condition to the latency of the target N2pc in the lateral-target/midline-distractor condition. As expected, the distractor N2pc clearly preceded the target N2pc (compare the respective N2pcs in Fig. 2 *B* and Fig. 2 *C*) by 99 ms, $t(15) = 5.79$, $p < .001$, $d_z = 1.45$, from which we infer that attention shifted from the distractor to the target.

This inference is rather indirect, because we isolated target and distractor N2pcs by presenting the respective other object on the midline and then compared the N2pc latencies across conditions. To ascertain that an attention shift occurred within a single condition, we examined electrophysiological activity for displays in which the target and distractor were presented on opposite sides: In this condition, both singletons would be expected to elicit an N2pc, which would be of opposite polarity (contralateral-distractor condition). Evidence of an attention shift from the distractor to target would consist of an N2pc to the distractor followed by an N2pc to the target (N2pc flip). An N2pc elicited by the contralateral distractor (i.e., a distractor N2pc) would emerge as a positive deflection in the difference wave plotted as a function of target side (Fig. 2 *D*). Indeed, there was such a positive deflection (0.56 µV), $t(15) = 3.65$, $p = .001$, $d = 0.91$, followed by a negative deflection (-1.67 µV), $t(15) = 4.84$, $p < .001$, $d = 1.21$, and their latencies differed significantly, by 117 ms, $t(15) = 5.98$, $p < .001$, $d_z = 1.49$, corroborating that attention shifted from the distractor to the target.

Of note, the timing of the target N2pc in the lateral-target/midline-distractor condition did not differ significantly from the timing of the distractor P_D in the midline-target/lateral-distractor condition (a 13-ms difference), $t(15) = 0.56$, $p = .293$, $d = 0.14$; we will elaborate on this post-hoc observation in the Discussion.

3.2.4 Lateralized ERPs sum up arithmetically

The negative deflection (target N2pc) on contralateral-distractor trials was increased in amplitude relative to the target N2pc on lateral-target/midline-distractor trials (by -1.07 µV; compare Figures 2B and 2D), $t(15) = 3.26$, $p = .003$, $d_z = 0.81$, and to the distractor-absent N2pc (by 0.80 µV; compare Figures 2A and 2D), $t(15) = 2.35$, $p = .016$, $d_z = 0.59$. As the timings of the distractor P_D and the target N2pc partly overlap and both would be visible as negative components in the contralateral-distractor ERP, the apparently enlarged target N2pc might simply reflect the summed activity elicited by two attentional mechanisms: attentional allocation towards the target (target N2pc) and active suppression of the contralateral distractor (distractor P_D). From the lateral-target/midline distractor and midline-target/lateral-distractor conditions, we can see what these two components look like in isolation. Given this, if our interpretation of the enlarged N2pc in the contralateral-distractor condition is correct, a composite of the two isolated ERPs should equal the contralateral-distractor ERP. As the distractor was on the side opposite to the target, it elicited a positive going N2pc and a negative-going P_D in the contralateral-distractor ERP. Consequently, we created a 'composite' contralateral-distractor ERP by subtracting the midline-target/lateral-distractor ERP from the lateral-target/midline-distractor ERP. As can be seen from Figure 3*A*, the reconstructed composite ERP and the actually observed ERP were virtually identical.

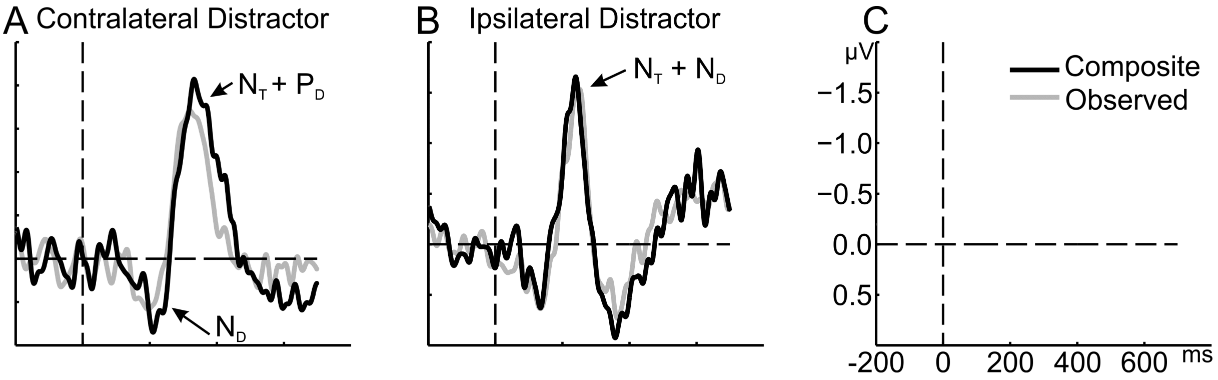

Figure 3. Composite ERPs constructed by subtracting or summing lateral-target/midline-distractor and midline-target/lateral-distractor ERPs. For comparison, the respective observed ERPs are re-plotted and overlayed in gray here. The strong overlap shows that lateralized ERPs induced by two lateralized objects are simply the sum of the lateralized ERPs evoked by each object in isolation.

In the ipsilateral-distractor condition, target and distractor were presented on the same display side. Here, too, a pronounced N2pc emerged (-1.46 μV), $t(15) = 6.89$, $p < .001$, $d = 1.72$ (Fig. 2 *E*). Again, this N2pc might be due to a partial overlap of two components, this time the target N2pc and the distractor N2pc (which would have the same sign in this condition). Indeed, the composite ERP (created by summing the two midline ERPs) was again virtually identical to the actually observed ERP (Figure 3*B*).

To quantify the overlaps of observed and composite ERPs, we correlated the voltage values of the composite and the respective observed grand-average ERPs across the diagnostic time range (100–500 ms after stimulus onset). These analyses confirmed the strong overlap with $R^2 = .84$, $p < .001$, and $R^2 = .90$, $p < .001$, for contralateral-distractor and ipsilateral-distractor ERPs, respectively. This illustrates that the four distractor-present ERPs coherently reflect the same underlying dynamics – just viewed from different perspectives.

3.2.5 Attention is captured on fast- and slow-response trials alike

RTs vary considerably not only between but also within conditions of visual-search tasks. Several studies have shown that qualitatively different attentional processes can occur on trials with fast versus slow responses (Hickey et al., 2010; Jannati et al., 2013; McDonald et al. 2013, Gaspar & McDonald, 2014). Thus, possibly, attention is allocated towards the distractor only on some trials. On these trials, responses should be slow and a distractor N2pc should be present. By contrast, trials on which attention moves directly to the target should go along with fast responses and no distractor N2pc. Accordingly, the distractor N2pc in the lateral-target/midline-distractor and the contralateral-distractor condition might be driven exclusively by slow-response trials. If, in contrast, attentional capture occurs on (virtually) every trial (as predicted for the present intra-dimensional distractor), we should observe a distractor N2pc independent of response speed and with an amplitude that is comparable between fast- and slow-response trials. To test this prediction, we performed a tertile split on RTs separately for each participant and condition (Fig. 4). As predicted, there was a significant distractor N2pc in the midline-target/lateral-distractor condition for fast-response trials (-1.19 µV), $t(15) = 3.28$, $p = .003$, $d = 0.82$, as well as for slow-response trials (-0.87 µV), $t(15) = 4.06$, $p < .001$, $d = 1.02$ (Fig. 4 *C*), and the distractor-N2pc amplitude did not differ significantly between fast and slow trials, $t(15) = 1.03$, $p = .318$, two-tailed, $d_z = 0.26$. The same pattern was observed for the distractor N2pc on contralateral-distractor trials (Fig. 4

D; fast: 0.43 μV, $t(15) = 2.16$, $p = .024$, $d = 0.54$; slow: 0.67 μV, $t_{(15)} = 3.58$, $p = .001$, $d = 0.90$; difference: $t(15) = 0.92$, $p = .373$, two-tailed, $d_z = 0.23$).

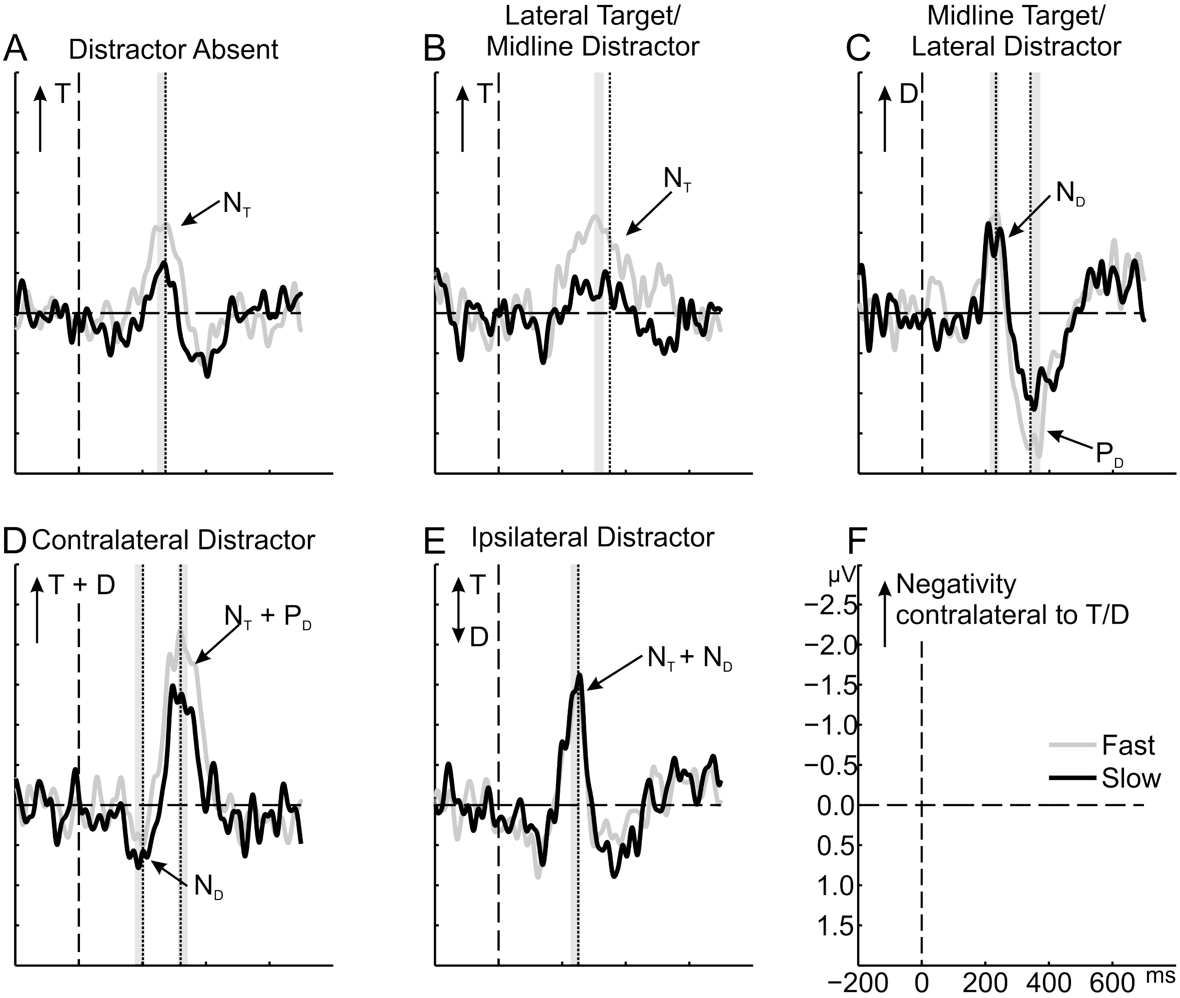

Figure 4. ERPs on trials with fast and slow responses (upper and lower tertiles). For details, see caption of Figure 2.

In a previous study, a distractor P_D was observed only for fast-response but not for slow-response trials (Gaspar & McDonald, 2014), indicating that participants suppressed the distractor only on some trials. Here, by contrast, the P_D (Fig. 4 *C*) emerged on fast (1.63 μV), $t(15) = 4.00$, $p < .001$, $d = 1.00$, as well as slow midline-target/lateral-distractor trials (1.07 μV), $t(15) = 4.56$, $p < .001$, $d = 1.14$, and, although Figure 4 suggests a tendency for larger P_D amplitudes on fast- relative to slow-response trials, the amplitudes did not differ significantly, $t(15) = 1.71$, $p = .107$, two-tailed, $d_z = 0.43$.

The only significant amplitude differences between fast- and slow-response trials emerged for target-N2pc amplitude in the distractor-absent condition (Fig. 4 *A*), $t(15) = 2.53$, $p = .023$, $d_z = 0.63$, and the lateral-target/midline-distractor condition (Fig. 4 *B*), $t(15) = 4.81$, $p < .001$, $d_z = 1.20$. This effect indicates that the variability in RTs is due to variation in target processing, rather than variation in attentional capture. One tentative interpretation of this post-hoc finding might be that N2pc amplitude reflects the amount of attentional resources allocated to the target or the precision of this allocation, and that responses are speeded when the amount or precision increases. Interesting as this effect may be, it was neither predicted a-priori nor is it related to the question at issue in the present study: attentional capture by the distractor – which is why we do not discuss it any further.

3.2.6 Distractor-P_D amplitude predicts distractor-interference effect on RTs

A complementary approach to test for ERP-behavior relationships makes use of interindividual differences (Vogel & Awh, 2008). Adopting such an approach, we can directly assess relationships between the distractor-interference effect in RTs (RTs on distractor-present trials minus RTs on distractor-absent trials) and electrophysiological markers of distractor processing (amplitude and latency of distractor N2pc and distractor P_D in the midline-target/lateralized-distractor condition). For the present data set, however, this analysis has to be interpreted with caution – for two reasons: First, we collected data from only 16 participants, while correlations tend to stabilize only with much larger sample sizes. Second, we had no strong a-priori hypotheses regarding ERP-behavior correlations, which is why this analysis must be regarded as exploratory. The distractor-interference effect on RTs was significantly correlated with P_D amplitude, $r = -.58$, $p = .020$, but neither with P_D latency, $r = -.09$, $p = .748$, nor with distractor-N2pc amplitude, $r = -.23$, $p = .382$, or latency, $r = -.21$, $p = .430$ (all tests two-tailed). The significant correlation indicates that stronger inhibition of the distractor (i.e., higher P_D amplitude) leads to less interference of the distractor with processes subsequent to the initial attentional deployment towards the distractor (attentional capture).

4 Discussion

Exploiting the high temporal resolution of the ERP methodology, we observed a clear sequence of attention mechanisms involved in overcoming capture by a salient distractor presented concurrently with the target: First, attention was allocated towards the distractor, as evidenced by a distractor N2pc. This distractor N2pc was observed in two independent conditions (contralateral-distractor and midline-target/lateral-distractor), thus indicating that the distractor reliably captured attention. Subsequently, the distractor was suppressed, as evidenced by a distractor P_D that emerged after the distractor N2pc. This distractor P_D indicates that attention did not automatically (or passively) move on to the next object on the priority map after the distractor was rejected as a non-target; rather, active top-down control seems to play a role in releasing attention from the distractor. Even though the distractor summoned attention first, the target was reliably attended, too, as evidenced by a target N2pc that emerged in two independent distractor-present conditions (contralateral-distractor and lateral-target/midline-distractor). Of note, in both conditions, the target N2pc emerged later in displays with, than in displays without, a distractor. This provides direct evidence that the distractor delayed attention allocation towards the target (instead of merely delaying some post-attentive process involved in response selection). The tight correspondence between ERPs as demonstrated by comparing observed with ‘composite’ ERPs indicates that all these attentional processes occurred in all distractor-present conditions of our study.

The sequence of distractor and target N2pcs led to a very distinctive ERP pattern when target and distractor were presented on opposite sides of the display: in an early time window, amplitudes were more negative contralateral to the distractor, while later, amplitudes were more negative contralateral to the target (Figure 2D). This N2pc flip indicates that – within the same display – attention shifted from the distractor to the target. Of note, the latency differences between the distractor and target N2pcs (117 ms) confirms earlier estimates for the time required for a reallocation of attention in visual search (100-150 ms; Woodman & Luck, 2003).

In contrast to the latency effects discussed thus far, we had no firm hypotheses regarding the respective timing of the distractor P_D and the target N2pc in the presence of a distractor. Possibly, the distractor first needs to be suppressed before attention can be allocated to the target. Alternatively, and in line with the data, suppression of the distractor and allocation of attention towards the target might occur in parallel (see Hickey et al., 2009, for a similar observation). Theoretically, this observation can be taken to indicate that an attention shift involves a combined process of suppression of the previously attended location and enhancement for the subsequently attended location, where the distractor P_D and the target N2pc reflect simply two sides of the same coin.

We observed attention allocation towards the distractor on both fast- and slow-response trials, with a distractor N2pc of equal amplitude in both types of trials. Importantly, trials on which attentional capture does not occur would give rise to short response times, without a distractor N2pc. Accordingly, a greater number of such no-capture trials would have contributed to the fast-response, as compared to the slow-response, ERPs. Consequently, if there had been a considerable number of no-capture trials, we should have observed a reduction of the N2pc amplitude in the averaged fast-response ERPs. At variance with this rationale, however, the distractor-N2pc amplitude was independent of response speed in both the contralateral-distractor and the midline-target/lateral-distractor condition. This suggests that the salient distractor was attended on a large majority of (if not all) trials, as would be expected if attentional capture is truly bottom-up driven and not penetrable by top-down control.

Note that a distractor N2pc has been observed by some previous studies (Burra & Kerzel, 2013; Hickey et al., 2006; Kiss et al., 2012), and a distractor P_D by others (e.g., Gaspar & McDonald, 2014; Hickey et al., 2009; Jannati et al., 2013; Sawaki et al., 2012). However, to our knowledge, no prior study has observed a distractor P_D following a distractor N2pc when distractor and target were presented concurrently. Instead, in all previous studies that reported a distractor P_D, the distractor was successfully suppressed before it could capture attention. Thus, our study is the first to provide evidence that a distractor is actively suppressed, after it did capture attention, to free attention for continuing search. – Before discussing how our design differed from that of these previous studies, it is instructive to first take a closer look at previous reports of a distractor N2pc.

Studies that have observed a distractor N2pc (in the midline-target/lateral-distractor condition) also observed a target N2pc (in the lateral-target/midline distractor condition; Burra & Kerzel, 2013; Gaspar et al., 2016; Hickey et al., 2006; Kiss et al., 2012). However, the target N2pc emerged at the same time as the distractor N2pc, whereas a delayed target N2pc should be observed if attention is first allocated towards the distractor and only then to the target. Thus, although these studies provide evidence for attentional capture by the distractor, it remains unclear whether attention was captured before, after, or in parallel with target processing in these studies. The only evidence for sequential allocations of attention on distractor and target was reported in the contralateral distractor condition of Hickey et al.'s (2006) Experiment 1: they observed an N2pc flip similar to the one reported here. However, a later re-analysis and extension of the data set cast doubt on the distractor-N2pc part of this flip (McDonald et al., 2013). Accordingly, in a comprehensive review of prior ERP studies on attentional capture, Jannati et al. (2013) concluded that "there is no N2pc flip when target and distractor are on opposite sides" (p. 1716)! Here, we not only observed such a flip, but additionally confirmed the implicated sequence of attention allocations (first distractor, then target) in conditions with one lateralized and one midline singleton object (see Figure 2).

Why did we observe this intriguing sequence of attentional mechanisms for the first time? We believe the most important reason is our choice of target and distractor features, which was intended to maximize distractor interference effects. Abundant evidence from our lab indicates (i) that people can selectively up- or down-weight whole feature dimensions (whereas selective weighting of specific features is dimensionally constrained; e.g., Found & Müller, 1996; Müller et al., 2003, 2009; Müller, Heller, & Ziegler, 1995; Sauter, Liesefeld, Zehetleitner, & Müller, 2017; Töllner et al., 2012; Zehetleitner et al., 2012), and (ii) that orientation is a particularly homogenous dimension in this regard (in comparison to, e.g., color, which was used by Gaspar & McDonald, 2014; color appears to consist of several, relatively independent sub-dimensions – see, e.g., Found & Müller, 1996, and Müller et al., 2003, for detailed discussions). We therefore defined both the target and the distractor as orientation singletons and indeed obtained extraordinarily strong distractor interference effects on RTs (225 ms, which is an order of magnitude larger than the typically observed interference of some 20 ms). This, probably, had two effects that are of importance for understanding the differences with respect to prior studies: First, target- and distractor-related ERP components were pulled apart, permitting a clearer picture of target and distractor processing to emerge. Second, as any relative down-weighting of the distractor feature was effectively prevented (by being defined in the target dimension), the distractor captured attention exceptionally reliably in the present design.

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7 Figure Captions

Figure 1. Schematic sample displays from each condition in the left-tilted-target group. Actual displays contained white bars on a dark gray background.

Figure 2. Difference waves at PO7/8 for the five conditions (*A*-*E*) and the scale (*F*; negative is up). Shadings indicate the mean-amplitude windows for the respective N2pc/P_D components. Analyzed components are labeled with N = negativity (N2pc) and P = positivity and subscripts T = target and D = distractor. Additionally arrows in the upper left of each panel indicate the position of the singletons. Negativities into the arrow direction indicate attention allocation towards the respective singleton location. The dotted vertical lines indicate mean component latencies (numerical latencies are given in parentheses below the respective component labels). To corroborate that the observed components were not due to saccadic activity, the residual horizontal-EOG difference waves are plotted in addition.

Figure 3. Composite ERPs constructed by subtracting or summing lateral-target/midline-distractor and midline-target/lateral-distractor ERPs. For comparison, the respective observed ERPs are re-plotted and overlayed in gray here. The strong overlap shows that lateralized ERPs induced by two lateralized objects are simply the sum of the lateralized ERPs evoked by each object in isolation.

Figure 4. ERPs on trials with fast and slow responses (upper and lower tertiles). For details, see caption of Figure 2.