Title:

Salient distractors induce a gradient of attentional suppression to cope with spatial and nonspatial filtering costs

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Abstract

Ideally, both enhancement of relevant and suppression of irrelevant information contribute to the deployment of visual selective attention. When stimuli are sufficiently salient, however, they can capture attention automatically before they are suppressed and thus interfere with the selection relevant stimuli. Here we analyzed how much interference is induced by distractors of varying distance to a target stimulus and how the visual system responds to that interference. We used an additional singleton visual search task in which participants had to search for a target and ignore a salient distractor presented at different distances to the target. We found behavioral evidence for spatial filtering costs: distractor interference increased with distractor proximity to the target, distractor interference was reduced when the target and distractor spatially coincided, and responses were slowed down when distractor and target were incompatible. Event-related potentials of the EEG paralleled this pattern: N2pc amplitude (reflecting target enhancement) increased while Pd amplitude (reflecting distractor suppression) decreased as the distance increased between target and distractor. This suggests less efficient enhancement of relevant and more effortful suppression of irrelevant information when target and singleton are closer, in line with the idea of increased neural competition for stimuli within the same receptive field. Distractors elicited an N2pc that was not affected by target-distractor distance, suggesting that varying attentional capture does not contribute to filtering costs. Importantly, when the distractor was presented in the same position as the target, we observed robust interference relative to a no-distractor condition. This evidence against a pure-capture account and suggests nonspatial interference contributes to the overall increased processing time when salient stimuli are presented. We additionally applied an inverted encoding model to track attentional subprocesses in a more fine-grained manner. Alpha-band topography tracked sustained top-down attention deployment towards targets, and transient but more pronounced attentional capture by the distractor. Below-baseline channel activity for distractors in the theta-band topography of the EEG signal tracked spatial suppression. In sum, our results show that salient distractors induce both spatial and nonspatial interference and that the visual system responds with a gradient of suppression that can account for distance-variant processing costs.

Introduction

Finding a friend at Times Square can be challenging because our visual system is confronted with more information than it can process. The selection of relevant information is a principle bottleneck in the visual processing stream and visual attention helps to address this constraint by filtering out irrelevant information (Duncan & Humphreys, 1989; Anne Treisman & Gelade, 1980; Wolfe, 1994). But which information is attended and gains access to limited resources? If we know that our friend is wearing a green shirt, selective attention enables us to focus on green objects, such that their neural representation is enhanced (Desimone & Duncan, 1995) and thus we find our friend more rapidly. This goal-oriented, voluntary attention deployment is also called top-down attention deployment (Folk et al., 1992; Folk & Remington, 2006; Wolfe et al., 2003). If attention was to only follow current goals, however, potentially relevant information that was not anticipated may go unnoticed. For example while looking for our friend, a traffic light might turn red, signaling us to immediately stop to avoid a collision with cars. Based on higher neural activity for stimuli that have a high local contrast (Itti & Koch, 2001), salient information like bright colored objects can capture our attention automatically. While this saliency-driven or bottom-up attention deployment may be generally adaptive, it can also result in unnecessary distraction by irrelevant salient information (Theeuwes, 1992; Theeuwes et al., 2000), for example when a colorful advertisement billboard captures our attention, momentarily interfering with the search for our friend.

The role of suppression in attentional deployment

To cope with such irrelevant salient items, suppression can be a crucial factor in overcoming attentional capture (Feldmann-Wüstefeld & Schubö, 2013; Sawaki & Luck, 2013), or avoiding attentional capture in the first place (Gaspelin & Luck, 2018; Feldmann-Wüstefeld et al., 2020). It has been suggested that in addition to enhancing relevant information, suppression of irrelevant information is an independent contributor to efficient attention deployment (Moran & Desimone, 1985; Reynolds & Heeger, 2009; Feldmann-Wüstefeld & Schubö, 2013; Gaspelin et al., 2015; Hickey

et al., 2009; Jensen & Mazaheri, 2010). Suppression of irrelevant stimuli is evident in basic neurophysiological processes. For example, direction-selective neurons in the middle temporal visual area (MT) of macaques show an increased firing rate when an object of their preferred direction is attended whereas neurons tuned to the opposite direction show a decreased firing rate, indicative of suppression (Treue & Trujillo, 1999). Similar results have been shown for areas V4 and IT in monkey cortices; neurons in these areas show a firing rate below baseline when a stimulus they are tuned for has to be ignored (Moran and Desimone, 1985, Chelazzi et al., 1993, Desimone and Duncan, 1995, Reynolds et al., 1999). Several studies showed that suppression contributes to efficient attention deployment (Awh et al., 2003; Caputo & Guerra, 1998; Gaspelin et al., 2015; Serences et al., 2004). For example, when participants expect a strong competition between the target and distractors, anticipatory suppression can compensate for the more challenging filtering and achieve a performance level comparable to easy filtering conditions (Awh et al., 2003). Current models of visual attention conceptualize selection to be based on a topographical 'priority map' on which all stimuli in the visual field are represented with a certain activity that determines how likely they are selected (Bundesen et al., 2005; Fecteau & Munoz, 2006; Itti & Koch, 2000; Wolfe, 2007). In terms of a priority map, suppression may be implemented as a negative activation for a stimulus representation (Failing et al., 2019), but current models of attention do not implement negative activations. For example in Guided Search (Wolfe, 2007), weights for specific features channels can assume various positive values reflecting the current pertinence of a color, shape, orientation etc., and thus facilitate attention deployment towards potential targets. These channels cannot assume negative weights, however, to steer attention away from irrelevant items. Instead the relative weight is what determines the guidance of attention.

One reason why current models of attention do not implement suppression may be the difficulty to distinguish between relatively low enhancement for distractors compared to a target (e.g., +3 versus +8) and actual suppression below baseline (e.g., -2 versus +3). In order to tell these possibilities apart, a valid baseline is required. In a series of studies, Gaspelin and colleagues (Gaspelin

et al., 2015, 2017; Gaspelin & Luck, 2018a) make a strong case for suppression by measuring attentional priority for a salient distractor and comparing it to attentional priority for neutral distractors as a baseline. They combined an additional singleton task, which is widely used to measure the competition between a relevant item and a salient but irrelevant item, with a probe task. The additional singleton task (Theeuwes, 1992, 2010) is a visual search task in which participants need to find a target (e.g., a diamond shape singleton) among homogeneous nontargets (e.g., circles). In some trials, an additional singleton (e.g., a red circle) is presented in addition to the nontargets, serving as a distractor. Such distractors typically cause a delay in response times. Gaspelin and colleagues (2015) presented an additional singleton search display in most of the trials and let participants search for a shape target and ignore a color distractor. In a subset of trials, unpredictable to participants, attentional priority throughout the visual field was probed by presenting letters in all items. In these trials, not only the target, but all items were suddenly relevant: Participants were to report as many letters as possible, regardless whether they were presented inside the target, inside the distractor or inside one of the nontargets that served as the baseline. Target letters were reported more often than nontarget letters, demonstrating a high priority of targets. Importantly, letters from distractor letters were reported least often, providing direct behavioral evidence for active suppression below baseline (Gaspelin et al., 2015). In line with this, saccades towards distractors were found to be less frequent than towards neutral nontargets in a follow-up study (Gaspelin et al., 2017).

Spatial and nonspatial filtering costs

While past work suggests that both enhancement and suppression contribute to attention deployment, there is much to be learned about the timing and spatial properties of these processes during target selection. A series of studies by Theeuwes (Theeuwes, 1991, 1992, 1994; Theeuwes & Godijn, 2002) demonstrated that the presence of an entirely task-irrelevant stimulus can induce severe interference in visual search for a target stimulus, as evident in prolonged RTs. This finding was initially taken as evidence for automatic, involuntary attentional capture by the distractor even if this

is detrimental to the current task and contrary to one's goals. Other studies provided evidence, however, that salient distractors do not necessarily capture attention but can be overruled in a top-down manner (Folk et al., 1992, 1992; Folk & Remington, 2006; Gaspelin & Luck, 2018b; Leber & Egeth, 2006; Feldmann-Wüstefeld et al., 2020). In this context, distractor-induced RT costs were argued to be due to nonspatial filtering costs rather than attentional capture by the distractor (Becker, 2007; Folk & Remington, 2006).

Evidence for nonspatial filtering costs comes from contingent capture studies (Folk & Remington, 1998; Folk & Remington, 2006). For example, Folk and Remington (1998) let participants search for a character of a specific color amongst uncolored characters. Prior to the onset of the search display, a distractor was presented at the upcoming target or upcoming nontarget location. When the distractor had the same color as the target, i.e., it matched the participants' search template, RTs were faster when presented at the target location, and slower when presented at a nontarget location, relative to distractor-absent trials that served as baseline. This suggests spatial filtering costs. When the distractor did not match the target color, i.e., it had an entirely task-irrelevant color, no such spatial congruency effect was found. Nonetheless, RTs were slower for distractor-present than distractor-absent trials, which led the authors to conclude that distractors without target-defining features still produce filtering costs, however nonspatial ones. In a follow-up study, Folk and Remington (2006) added a character to the distractor that could either match or not match the target character. They found that distractors induced longer RTs in the absence of compatibility effects (i.e., the distractor identity does not affect processing of the target), suggesting that the distractor interferes with target enhancement without spatially deploying attention to the distractor location. Moreover, even when a singleton does not elicit an N2pc, indicative of absent attention deployment, the latency of the target-N2pc increases, indicative of delayed processing of the target (Wykowska & Schubö, 2011).

Other research has demonstrated a strong spatial component in distractor interference. First, several EEG studies found that distractors that do not share any features with the target elicit an N2pc

component, suggesting they captured attention, at least in a considerable subset of trials (Hickey et al., 2009; Liesefeld et al., 2017; Feldmann-Wüstefeld et al., 2016; Feldmann-Wüstefeld & Schubö, 2013; Hilimire & Corballis, 2014; Kiss et al., 2012; Sawaki & Luck, 2013). Second, several studies manipulated the distance between targets and distractors, and then acquired neural or behavioral measures of target selection (Caputo & Guerra, 1998; Gaspar & Mcdonald, 2014; Hickey & Theeuwes, 2011; Koch et al., 2013; Kwak et al., 1991; Mounts, 2000; Starreveld et al., 2004; Theeuwes et al., 2004). For example Mounts (2000) measured RTs to targets in an additional singleton task as a function of distance between target and distractor. The results indicated that distractor interference, i.e., the RT costs induced by the presence of the distractor, was strongest for distractors in immediate proximity to the target whereas more distant singletons did not affect target processing as much. Gaspar and McDonald (2014) found a similar behavioral pattern and also measured the target N2pc as a function of distance between target and singleton: The N2pc amplitude decreased with prosimity to the distractor. The authors concluded that distractor interference arises from the neural ambiguity when target and salient distractor are presented within the same receptive field. That is, suppression of the distractor and enhancement of the target are in direct opposition and impair the filtering process necessary to extract relevant information.

One study found that search difficulty affected the proneness of attention deployment to involuntary attentional capture. When search was difficult because the target was presented in a noisy context, a salient distractor captured attention whereas no capture was observed under easy search conditions with little noise (Feldmann-Wüstefeld & Schubö, 2013). This is in line with the notion that nonspatial filtering and attentional capture can co-occur and their relative contribution to attention deployment is dependent on attentional control settings induced by experimental factors such as feature and spatial uncertainty (Becker, 2007). The role of suppression in overcoming spatial and nonspatial filtering has not been thoroughly investigated. Previous studied examined the role of suppression in avoiding attentional capture (Feldmann-Wüstefeld et al., 2020; Gaspelin et al., 2015; Gaspelin & Luck, 2018a; van Moorselaar & Slagter, 2019; Wang & Theeuwes, 2018) or overcoming

attentional capture (Burra & Kerzel, 2014; Sawaki & Luck, 2013). The suppression of irrelevant information, however, may also play a crucial role at moderating spatial and nonspatial filtering costs. For example, it may be that distractors near targets do not capture attention more, but rather induce a higher need for suppression. The goal of the present study was to measure the gradient of both interference and suppression as a response to interference.

Neural markers of attentional enhancement and suppression

Neurally, two EEG/ERP components have been of great importance to investigate attentional subprocesses: The N2pc as a marker of enhancement and the Pd as a marker of suppression. The N2pc is a negativity contralateral to an attended item and can be elicited both by targets and salient distractors (Burra & Kerzel, 2014; Eimer, 1996; Feldmann-Wüstefeld & Schubö, 2013; Hilimire & Corballis, 2014; Luck & Hillyard, 1994; Mazza et al., 2009). Ideally, the N2pc is measured in trials in which the target is presented laterally and the distractor on the vertical midline which renders the distractor "invisible" to the lateralized ERP and the N2pc merely reflects target processing (Hickey et al., 2009). By swapping the position of target and salient distractor, the processing of the salient distractor can be isolated. When the distractor is presented laterally and the target on the vertical midline, a distractor-N2pc is sometimes found (Feldmann-Wüstefeld et al., 2016; Hilimire & Corballis, 2014; Kiss et al., 2012; Liesefeld et al., 2017; Sawaki & Luck, 2013) indicative of attentional capture by the distractor. Importantly, lateral distractors also elicit a Pd (distractor positivity), a positivity contralateral to the salient distractor that is thought to index active suppression (Hickey et al., 2009; see also Burra & Kerzel, 2014; Feldmann-Wüstefeld et al., 2015; Gaspelin & Luck, 2018; Liesefeld & Müller, 2019; Sawaki & Luck, 2013; Weaver, van Zoest, et al., 2017).

A large body of evidence links the Pd to suppression. For example, in trials in which a distractor did not cause RT costs (indicating it has been successfully suppressed) no Pd was observed. However, in trials with high RT costs, suggesting failed suppression, an inverse Pd (i.e., a distractor-N2pc), indicative of involuntary attentional capture was observed (Sawaki et al., 2012). In line with this, a

study combining EEG and eye tracking showed that when observers erroneously made an eye movement to a distractor, no Pd was observed but when they correctly made a saccade to the target, a Pd was observed contralateral to the distractor (Weaver, Zoest, et al., 2017). Moreover, within individuals the Pd is larger in fast trials (Feldmann-Wüstefeld et al., 2016; Gaspar & McDonald, 2014), suggesting that the Pd reflects effective suppression that allows rapid target identification. A macaque study combining ERPs and single-unit recordings showed an equivalent of the Pd in the neuron discharge rate that was closely related to the suppression of a salient irrelevant item (Cosman et al., 2018). More evidence linking the Pd to suppression comes from studies probing attention deployment in additional singleton tasks. For example the amplitude of the distractor-elicited Pd in the regular search trials is positively correlated with the amount of behavioral suppression measured in probe trials (Gaspelin & Luck, 2018). One study measured the Pd amplitude as a function of whether participants attended a distractor or not (Feldmann-Wüstefeld et al., 2020). The experimenters used a task similar to the probe trials from Gaspelin et al. (2015) in which each item in an additional singleton task had a unique identity (digits). Participants were to always report the shape target digit while ignoring digits inside nontargets and a color distractor. Experimenters provoked errors by using a limited exposure duration and masking digits. In a critical time window, no Pd was observed in those trials in which participants erroneously reported the distractor compared to those trials in which they reported a less salient nontarget (baseline) or target (correct response). This suggests that the Pd is the neural correlate of the suppressive process that lacked when participants erroneously reported the distractor identity.

Together, N2pc and Pd can be used to track the subprocesses of attention deployment: the presence of a target-N2pc reflects enhancement of the target (i), a distractor-N2pc reflects involuntary attentional capture by a distractor (ii) whereas the presence of a Pd indicated the active suppression thereof (iii). Analyses of the latency of these components have revealed the chain of attentional mechanisms that are evoked when competing stimuli are present in the visual field (Liesefeld et al.,

2017): Attention is first captured by the most salient item, then suppression of the most salient item is applied. Suppression of irrelevant and enhancement of the relevant items can run in parallel.

One limitation of the N2pc and Pd components is that they are limited in their spatial precision to the granularity of hemifields, and cannot differentiate between various positions within a hemifield. Recent computational advances using multivariate analyses of EEG activity allow greater precision in tracking the attended location (Fahrenfort et al., 2016; Foster, Bsales, et al., 2017; Foster, Sutterer, et al., 2017). For example. Foster and colleagues (2017) used the alpha band activity in the EEG signal in a subset of trials to train an inverted encoding model (IEM) with 8 'channels', each optimized for one of 8 locations used in a cueing experiment. By using the activity of these 8 channels in an independent set of trials, they could reconstruct graded attention deployment as a peak at the cued location and decreasing channel activity at more distant locations. Previous research limited IEM to tracking attention deployment towards targets. In the present study we will use an IEM to track attention deployment towards both targets and distractors.

Rationale of the present study

Aim of the present study was to measure spatial and nonspatial interference during the deployment of visual attention and assess how the visual system uses suppression to cope with this interference. We used an additional singleton visual search task and presented target and distractor at varying distances to assess how much interference occurs. According to the neural ambiguity account (Desimone & Duncan, 1995; Hickey & Theeuwes, 2011; Luck, Girelli, et al., 1997), it is more difficult to process the target stimulus with a salient distractor in the same receptive field. Thus we first expected to replicate earlier findings showing longer RTs with increasing target-distractor proximity (e.g., Mounts, 2000). Second, we expected the target-N2pc to decrease in amplitude with increasing target-distractor proximity, in line with earlier studies showing less efficient attention deployment towards targets presented near distractors (Gaspar & Mcdonald, 2014). Importantly, and contrary to previous studies, we also examined how distractor-elicited ERP components respond to

target-distractor distance. This allowed us to track the gradient of attentional enhancement and suppression. The distractor-N2pc may be larger for distractors near the target. This would suggest that the more pronounced interference for distractors nearby targets is at least partially due to more attentional capture. Alternatively, attentional capture may not be affected by target-distractor proximity, but the additional filtering costs are due to an additional need for suppression. Accordingly, distractors near the target may require more suppression to allow sufficient processing of the target. In that case, the Pd component should be sensitive to target-distractor distance; the Pd amplitude should increases with proximity of a salient distractor to the target.

Importantly, target and distractor location were entirely unyoked, i.e., they could also appear in the same position (distance-zero trials). Distance-zero trials may provide further evidence for nonspatial filtering costs. It was suggested that the ratio of distractor-presence costs (faster responses for distractor-absent compared to distractor-present trials) to same-location benefits (faster responses for distance-zero compared to distance > 0 trials) are indicative of nonspatial filtering (Becker, 2007). The logic behind this is that distractor-presence costs serve as a measure of the overall interference whereas the same-location benefit serve as a measures of spatial filtering – the more attention is captured by the most salient stimulus, the more should a target benefit from being presented in the same position. For example, if distractors delay RTs by 30 ms, but the advantage for distance-zero trials compared to distance > 0 trials is only 5 ms, this would indicate a relatively small contribution of spatial filtering costs to overall interference.

The neural data obtained in distance-zero trials will also be crucial to reveal spatial and nonspatial filtering costs. Targets and distractors in the same location should produce high activations on the priority map as due to a redundancy gain, i.e., a shape and color singleton coincide (Krummenacher et al., 2002) and because top-down and bottom-up factors dovetail (Fecteau & Munoz, 2006; Itti & Koch, 2001; Wolfe, 2007). A larger N2pc for distance-zero than distance > 0 trials would indicate that the spatial coincidence of target and distractor attract attention more than the target alone, in line with the attentional capture account (Theeuwes, 2010) and previous behavioral

findings showing improved performance when targets and singletons coincide (Turatto et al., 2004; Yantis & Egeth, 1999). The N2pc results, however, need to be assessed in the context of the behavioral benefits. It is conceivable that no behavioral benefit in distance-zero trials will be observed despite an increased N2pc amplitude through time-consuming resolution of interference independent of the distractor position (Becker, 2007; Folk & Remington, 1998; Folk & Remington, 2006; Kahneman et al., 1983; Wykowska & Schubö, 2011). For example attention may be deployed efficiently towards the target/distractor location, but the identification of the target is deteriorated due to the presence of irrelevant salient information (Kahneman et al., 1983), regardless where that information is presented. Several studies have identified an additional, early positivity contralateral to distractors, the posterior positivity contralateral (Ppc), also referred to as early Pd that peaks around 80-150 ms and may reflect early suppression (Barras & Kerzel, 2017; Feldmann-Wüstefeld & Vogel, 2019; Weaver, Zoest, et al., 2017) or saliency-induced bottom-up processing differences (Fortier-Gauthier et al., 2012; Gokce et al., 2014; Jannati et al., 2013). The Ppc will be analyzed in an exploratory manner to identify potential differences in early suppression due to increased neural ambiguity when target and distractor are in close proximity.

We used IEMs to complement ERP analyses. While the N2pc and Pd can be used to track the time point and amount of attentional enhancement/suppression, IEMs have the advantage of tracking cognitive processes independent of current visual stimulation, e.g. in a anticipatory manner (Feldmann-Wüstefeld & Awh, 2020) or sustained manner, i.e. long after stimulus presentation (Fahrenfort et al., 2016; Foster, Sutterer, et al., 2017). This will allow us to track the time course and spatial gradient of attention deployment more precisely, and importantly, for distractor and target simultaneously. For example, it has been suggested that a salient distractor is initially attended for a brief period of time whereas top-down driven attention deployment towards the target eventually prevails (Kim & Cave, 1999; Theeuwes et al., 2000). We hypothesize that targets will be represented in spatially-selective oscillatory activity, replicating earlier studies (Foster, Sutterer, et al., 2017). In addition, we may be able to train the model to also represent distractor positions. When training the

model on target location and testing it on distractor location, channel activity may be increased at distractor locations, suggesting the IEM can track attentional capture in addition to voluntary attention deployment. This would allow us to track and compare the time course of attentional enhancement of targets and distractors. In addition, as we expect distractors to be actively suppressed, channel activity may also be reduced at distractor locations which would be the equivalent of a Pd and reflect suppressive activity.

Overview Experiments 1-4

Aim of the present study was to measure spatial and nonspatial filtering costs induced by salient distractors with a focus on how (i) attentional enhancement and (ii) attentional suppression are modulated by the distance between target and distractor, i.e. the neural ambiguity. First, in two behavioral experiments we revised the additional singleton paradigm to statistically unyoke target and distractor location, i.e. to present targets and distractors in the same location in 1/d of the distractor-present trials where d = display size. This was necessary to measure a potential same location benefit, but also to make the distractor location non-predictive regarding the target location which can induce strategies that affect attentional capture (Becker, 2007; Yantis & Egeth, 1999). Furthermore, unyoked target and distractor locations were crucial to achieve an unbiased IEM. To elaborate, when a multivariate model is trained on a target location in trials in which target and distractor are never presented at the same location, the model might pick up on the location that does not show the distractor rather than on the location that shows the target, biasing channels in an unpredictive manner.

We used Experiment 1 and 2 to ensure classic additional singleton costs (Theeuwes, 1992, 2010) as well as increasing RT costs with proximity to the target (e.g., Gaspar & McDonald, 2014) would be observed in the revised additional singleton task. In singleton-present trials of Experiment 1, the target was red in 1/d of the trials while one of the nontargets was red in the remaining d-1/d of the trials. In singleton-present trials of in Experiment 2, an additional red ring was presented around

the target in 1/d of the trials and around one of the nontargets in d-1/d of the trials (i.e., one of the items was a triple-compound stimulus). We then used the triple-compound variant in two EEG experiments. In Experiment 3, the distractor consistently had the same color throughout the experiment whereas in Experiment 4, it had a different color when it was presented in the target location, which allowed observers to rely on color as a defining property of the target. As behavioral results were virtually identical in Experiment 3 and 4, we collapsed across these experiments to achieve a higher statistical power for EEG analyses.

To anticipate the results, the Pd component in the event-related potential (ERP) increased in amplitude as target-distractor distance decreased while N2pc to the target declined as target-distractor distance decreased. Distractor-N2pc remained unaffected by distance. This was paralleled with increased distractor interference (measured with reaction time) for nearby targets and singletons. Moreover, IEM analyses found that spatial channel activity in the alpha band tracked both sustained top-down driven attentional deployment towards the target and transient bottom-up driven attentional capture by the distractor. Spatial channel activity in the theta band additionally tracked the gradient of distractor suppression. While these results indicate spatial interference and resolution thereof, behavioral results also indicated nonspatial filtering costs: response times in singleton-absent trials were faster than in trials in which singleton and target coincided

Method Experiment 1 & 2

Participants

In Experiment 1 (double compound), twenty volunteers aged 19-31 years (M = 21.5, SD = 3.2), thirteen female, all right-handed, participated. In Experiment 2 (triple compound), twenty-one volunteers aged 18-31 years (M = 23.5, SD = 4.5), eleven female, one left-handed participated. Participants were naive to the paradigm and objectives of the study and were paid ~$10 per hour. Both experiments were conducted with the written understanding and consent of each participant. The University of Chicago Institutional Review Board approved experimental procedures.

Apparatus

Participants were seated in a dimly lit, electrically shielded and sound attenuated chamber. Participants responded with button presses on a standard keyboard that was placed in front of them. Stimuli were presented on an LCD computer screen (BenQ XL2430T; 120 Hz refresh rate; 61 cm screen size in diameter; 1920 × 1080 pixels) placed at 75 cm distance from participants. An IBM-compatible computer (Dell Optiplex 9020) controlled stimulus presentation and response collection using MATLAB routines.

Stimuli

All stimuli were presented on a gray background (RGB: 128-128-128). Search displays always showed six items presented equidistantly on an imaginary circle (3° radius) around a black central fixation cross (0.5° diameter, RGB: 0-0-0), see Fig. 1. Items positions were fixed with two items on the vertical midline and two items in each hemifield. One of the items was a diamond (2.1° diameter, 2 pixels line width), serving as a target stimulus. The other five items were nontarget circles (1.6° diameter, same area as target, 2 pixels line width, RGB: 64-64-64). In distractor-absent trials, all items were dark grey (RGB: 64-64-64) and the target appeared equally often at one of the six positions. In distractor-present trials of Experiment 1, one of the six items was red (RGB: 255-0-0). The singleton was equally often presented in each location, i.e., the target was a red diamond in 1/6 of the distractor-present trials. In distractor-present trials of Experiment 2, an additional empty red circle

(2.4° diameter, 2 pixels line width, RGB: 255-0-0) appeared equally often around any one of the six items, i.e., around the target in 1/6 of the distractor-present trials. The 36 combinations of target and distractor locations appeared equally often in distractor-present trials. Within each of the six items was a dark gray line that was either vertical or horizontal (0.75° length, RGB: 64-64-64). Horizontal and vertical lines were used equally often for the target. In addition, in distractor-present trials in which the distractor was presented at a location different from the target location, the four combinations of horizontal and vertical lines were used equally often for the target and the distractor. The orientation of the lines within the remaining nontargets was randomly assigned with as many horizontal as vertical lines (or as close as possible).

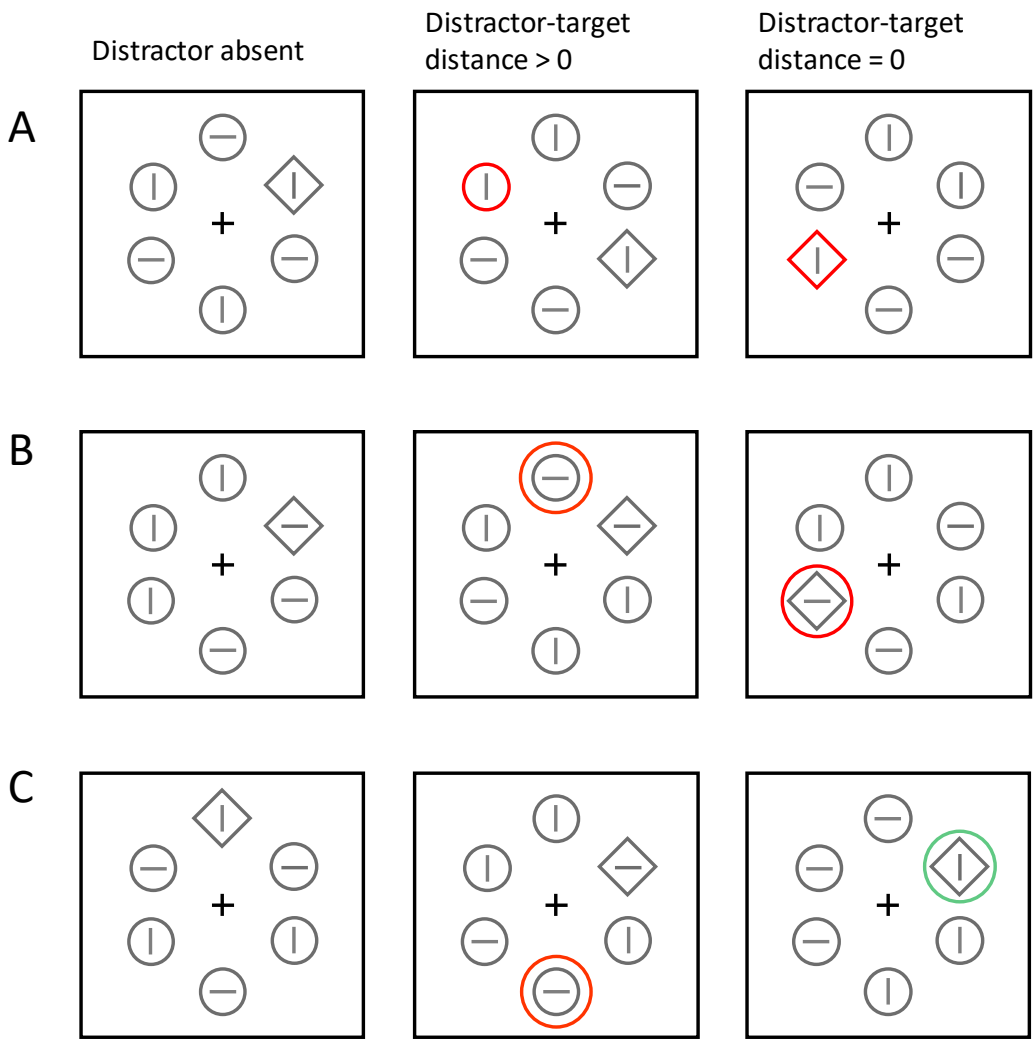

Figure 1. Visual search displays used for Experiment 1 **(A)**, Experiment 2 & 3 **(B)** and Experiment 4 **(C)**. Participants had to find the diamond-shaped target and report the orientation of its embedded line with a key press. In half the trials, all items were grey (distractor absent trials). In the other half of the trials, a color singleton (red/green ring), serving as a distractor, was presented equally likely in one of the six positions. This means the singleton was in a distractor position in 5/6 of singleton-present trials (distance > 0) and in a target position in 1/6 of singleton-present trials (distance = 0). In Experiment 4, different color were used for distance > 0 and distance = 0 trials.

Procedure

Each trial started with a display showing the fixation cross and no other objects for a duration of 500 ms (see Fig. 2). Subsequently, the search display was shown for 200 msec in addition to the fixation cross. Finally, a response display with the fixation cross only was shown until participants responded or for a maximum of 1000 msec. Participants were instructed to report the orientation (horizontal or vertical) of the line within the diamond-shaped target by pressing a key corresponding to each orientation (key assignments were counterbalanced across participants). Their responses were limited to a time window of 1200 msec (search display + response display), and responses made after this period were not counted. If participants did not respond within this time window, a message reading "Too slow" was shown for 500 msec. After this message, or after participants responded, a blank screen was shown for a duration of 1000 msec. Then the next trial began by showing a new fixation cross.

Participants were given the opportunity to practice the task before the experiment began. Once participants reached 75% accuracy and felt comfortable doing the task, they began the experiment. The experiment consisted of 24 blocks of 36 trials (864 trials in total). Half the trials (432) were singleton-absent, the other half (432) were singleton-present. All trials were presented in random order across the entire experiment. After each block, participants were given feedback about

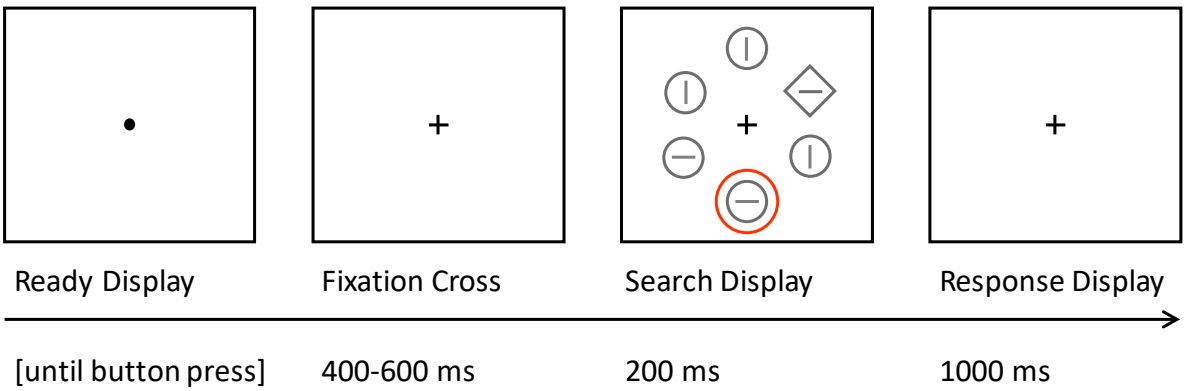

Figure 2. Trial procedure. Each trial started with a Ready Display. Participants had to fixate the central dot and press a key when ready. Upon key press a fixation cross followed for 400-600 ms before the search display was presented for 200 ms. The subsequent Response display only showed a fixation cross. Participants had to respond during the Search Display or Response Display presentation (i.e., within 1200 ms). The Response display was followed by an inter-trial interval showing a blank screen for 1000 ms (Experiment 1) or 800-1200 ms (Experiment 2&3). The Ready Display was not used in Experiment 1 & 2.

their performance (percent correct, number of slow trials, and if a new "high score" was achieved for accuracy during that block). Following feedback, there was a mandatory ten second break after which participants could choose to either immediately continue to the next block or to extend their break.

Design & data analysis

There were two main conditions: distractor-absent and distractor-present trials. Since trials with coinciding target and distractor constitute a special case, three conditions were considered: distractor-absent, distractor present, distractor-target distance = 0 (from here on "Dist=0"), distractor-target distance > 0 (from here on "Dist>0"). Accordingly, mean response times (RTs) and error rates were forwarded to a one-way ANOVA for repeated measures with three factor levels. In addition, RTs in distractor-present trials were analyzed as a function of distance between target and distractor. As there were six positions and target and distractor could be presented at the same location, there was a total of four distances used (0, 1, 2, 3). For all RT analyses, only correct trials were used. For all experiments, Greenhouse-Geisser correction was applied where appropriate. Effect sizes are reported as partial eta squared (η^2) for ANOVAs and Cohen's d for t-tests.

Results Experiment 1

Distractor position affected RTs (see Fig. 8), $F(2,38) = 23.7$, $p < .001$, $\eta^2 = .56$. Follow-up t-tests show that distractor-absent trials (555 ms) were faster than Dist>0 trials (582 ms), $t(19) = 8.4$, $p < .001$, or Dist=0 trials (566 ms), $t(19) = 2.8$, $p = .012$. Besides, Dist=0 trials were faster than Dist>0 trials, $t(19) = 3.5$, $p = .002$. Distractor position also affected accuracy, $F(2,38) = 3.3$, $p = .047$, $\eta^2 = .15$. Follow-up t-tests show that singleton-absent trials (90.7%) were more accurate than Dist>0 trials (88.6%), $t(19) = 2.3$, $p = .033$, but not less error prone than Dist=0 trials (90.8%), $t(19) = 0.1$, $p = .897$. Dist>0 trials were marginally more error prone than Dist=0 trials, $t(19) = 2.1$, $p = .053$.

The distance between target and distractor affected RTs, $F(3,57) = 13.7$, $p < .001$, $\eta^2 = .42$. All direct comparisons between distances (0, 1, 2, 3) were reliable (all $p \leq .020$) except for distance 0 and 3 ($p = .382$). The distance between target and distractor affected accuracy ($M_0 = 90.8$ %, $M_1 = 87.9$ %,

M_2 = 88.6 %, M_3 = 90.0 %), $F(3,57) = 2.9$, $p = .041$, $\eta^2 = .13$. Only the direct comparisons between distance 0 and 1 was reliable ($p = .030$), none of the other direct comparisons were reliable (all $p \geq .051$).

In compatible trials (target and distractor line of same orientation) RTs were equally long (M = 581 ms) as in incompatible trials, (M = 584 ms), $t(19) = 0.7$, $p = .236$, $d = 0.04$. Accuracy, however, was higher in compatible (M = 89.5%) than in incompatible trials (M = 87.7%), $t(19) = 1.9$, $p = .040$, $d = 0.18$.

Results Experiment 2

Distractor position affected RTs, $F(2,40) = 33.8$, $p < .001$, $\eta^2 = .63$ (see Fig. 3, upper left panel). Follow-up t-tests show that singleton-absent trials (587 ms) were faster than Dist>0 trials (633 ms), $t(20) = 8.8$, $p < .001$, or Dist=0 trials (618 ms), $t(20) = 6.1$, $p < .001$. Furthermore, Dist=0 trials were faster than Dist>0, $t(20) = 2.2$, $p = .042$. Distractor position also affected accuracy, $F(2,40) = 4.5$, $p = .017$, $\eta^2 = .18$. Follow-up t-tests show that singleton-absent trials (93.3%) more accurate than Dist>0 trials (90.7%), $t(20) = 3.0$, $p = .006$, but only marginally less error prone than Dist=0 trials (91.8%), $t(20) = 1.9$, $p = .073$. Dist>0 trials were as accurate as Dist=0 trials, $t(20) = 1.2$, $p = .256$.

The distance between target and distractor affected RTs, $F(3,60) = 18.7$, $p < .001$, $\eta^2 = .48$ (see Fig. 3, lower left panel). All direct comparisons between distances (0, 1, 2, 3) were reliable (all $p \leq .025$) except for distance 0 and 3 ($p = .553$) and distance 0 and 2 ($p = .511$). The distance between target and distractor did not affect accuracy (M_0 = 91.8 %, M_1 = 89.7 %, M_2 = 91.4 %, M_3 = 91.3 %), $F(3,60) = 1.6$, $p = .196$, $\eta^2 = .08$. No direct comparisons between distances was reliable (all $p \geq .097$).

In compatible trials, RTs were shorter (M = 625 ms) than in incompatible trials, (M = 641 ms), $t(19) = 3.8$, $p < .001$, $d = 0.20$. Analogously, accuracy was higher in compatible (M = 92.3%) than in incompatible trials (M = 89.1%), $t(19) = 3.0$, $p = .003$, $d = 0.53$.

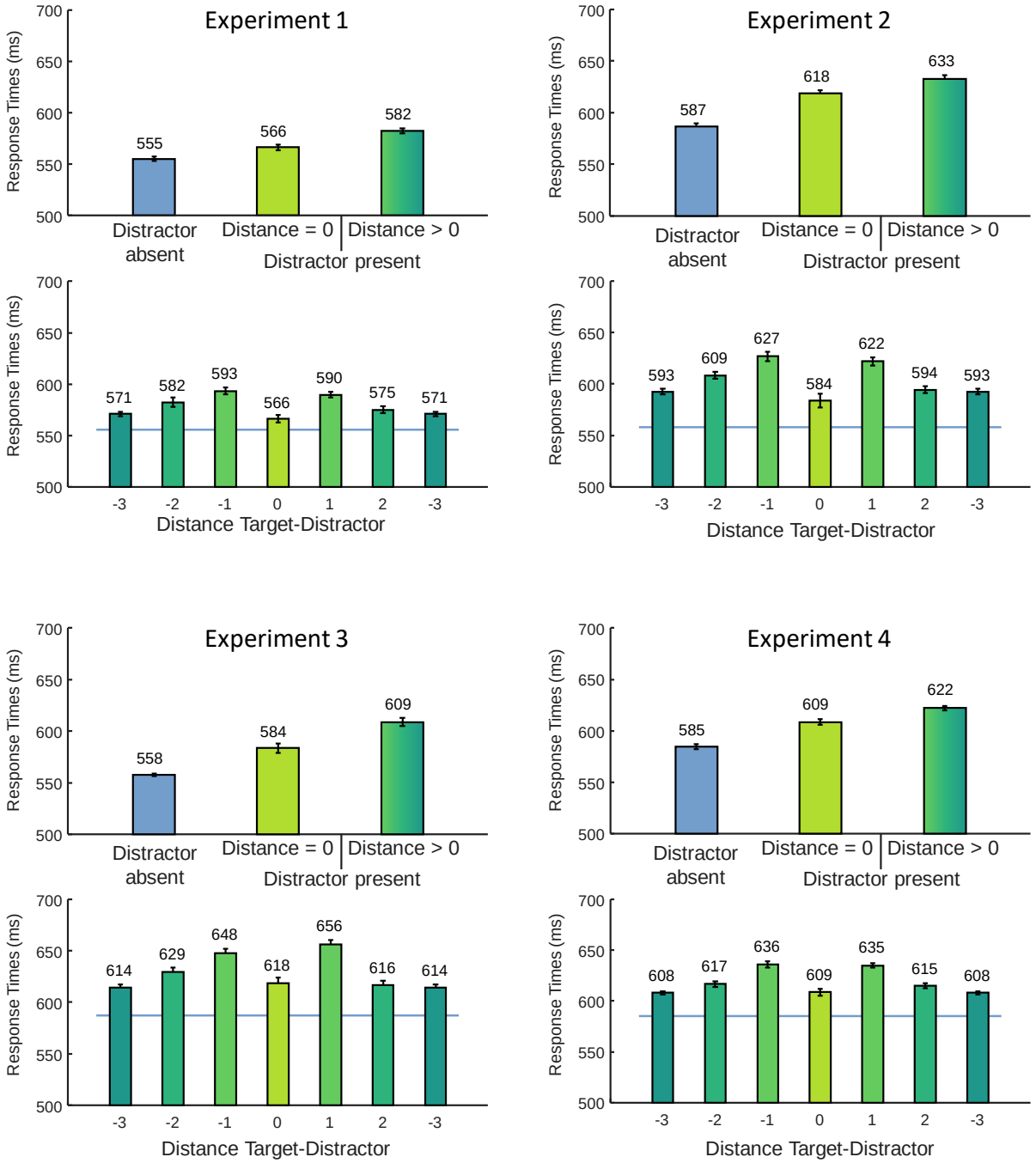

Figure 3. Behavioral results Experiment 1-4. The upper panels shows RT as a function of trial type (distractor absent, distractor-target distance = 0, distractor-target distance > 0). The lower panels show RT as a function of distance between target and distractor in distractor-present trials (blue line depicts RT in distractor-absent trials for comparison). Negative numbers represent counterclockwise distances, positive numbers clockwise distances. Distance 0 refers to trials in which target and distractor appeared at the same location (Experiments 2-4) or the target was the color singleton itself (Experiment 1). Error bars denote standard errors of the mean, corrected for within-subjects variability (Cousineau, 2005).

Intermediate discussion

We could replicate earlier findings showing that an additional singleton results in RT costs (Theeuwes, 1992, 2010; Feldmann-Wüstefeld & Schubö, 2013; Sawaki & Luck, 2013). The RT costs were most pronounced for singletons adjacent to the target and monotonically decreased to more distant locations, replicating earlier findings (Caputo & Guerra, 1998; Gaspar & McDonald, 2014; Koch et al., 2013; Kwak et al., 1991; Starreveld et al., 2004; Theeuwes et al., 2004). The results indicate spatial interference as the strength of capture declines as target-distractor distance increases. Experiment 1 showed RT costs and distance effects when the target was the additional singleton at chance level (1/6 of trials), i.e., when there was no incentive for participants to attend red. Experiment 2 replicated the results with triple compound stimuli, i.e. when an additional red ring was presented around the target in 1/6 of the trials.

Our data indicate a strong spatial component in filtering. First, we observed same location advantage of 16 ms (compared to overall interference of 27 ms) in Experiment 1 and a same location advantage of 15 ms (compared to overall interference of 46 ms) in Experiment 2. Compared to distance-one, same location benefits were even more pronounced: 26 ms in Experiment 1 and 40 ms in Experiment 2. These results suggest attentional capture by the distractor. Second, we found a distance-dependent modulation of the distraction effect. As pointed out by Folk and Remington (1998, p.857) "if the distraction effect in visual search does not reflect a shift of attention, the magnitude of the effect should not vary as a function of the distance between the distractor and target." Thus our data provide strong evidence for a shift of attention, i.e., spatial filtering. Third, we found compatibility effects in accuracy (Experiment 1 and 2) and RT (Experiment 2), i.e. the target identification was more accurate/faster when distractor and target both had a vertical or both had a horizontal line. Compatibility effects are indicative of attention deployment towards the distractor as the distractor identity presumably only affects target processing if the distractor was attended (Folk & Remington, 1998; Theeuwes & Burger, 1998).

In addition, however, our data also provide evidence for nonspatial filtering. Surprisingly, RTs in distance-zero trials were longer than in distractor-absent trials (11 ms in Experiment 1 and 31 ms in Experiment 2). Only few previous visual search studies tested how presenting target and additional singleton at the same location would affect attention deployment which makes it difficult to reconcile these findings. Some visual search studies showed distractors in all trials and found fastest performance when target and distractor coincided – but distractor absent trials were not used as a baseline (Theeuwes & Godijn, 2002; Turatto et al., 2004; Yantis & Egeth, 1999). One study used singleton absent and singleton targets in the same visual search task (Becker, 2007). When singleton color was kept constant (as in the present study), RTs were 13-23 ms faster in singleton absent compared to singleton target trials (Becker, 2007; note that this was not statistically tested as Becker's study focused on a different research question). Same-location costs were also found in contingent capture paradigms (Carmel & Lamy, 2014; Eimer, Kiss, Press, & Sauter, 2009; Lamy, Leber, & Egeth, 2004; Schoeberl, Ditye, & Ansorge, 2018). However, as distractor and target are not presented simultaneously in this task, detrimental target processing at the distractor location were accounted for by object updating/integration of target and distractor over time (Carmel & Lamy, 2014) or inhibition of return (Belopolsky et al., 2010). In the present study, where target and distractor were presented simultaneously, same location costs can be taken as evidence for nonspatial filtering. For example, Folk and Remington (1998, p. 848) argue that "an irrelevant object can produce a delay in the deployment of spatial attention to a relevant object without eliciting a shift of attention to itself". This could explain RT costs in distance-zero trials in which a shift of attention towards the distractor may happen, but could alone not explain the RTs costs compared to distractor-absent trials. For example Treisman and colleagues (1983) found that the reading latency for words was shorter when colored shapes were presented in the same rather than in different positions. Words in the same positions as colored shapes, however, still produced longer reading latencies than trials without colored shapes. The delay in reading, or target processing in the present study, may be due to disruption or delay of target feature extraction induced by an additional object that competes for

attentional resources, even if it is presented at the same location (Folk & Remington, 1998; Kahneman et al., 1983; Treisman et al., 1983).

In sum, Experiments 1 and 2 show that both spatial and nonspatial interference seem to affect attention deployment. In the following (Experiment 3 & 4), we will adapt our triple compound search task for EEG measurements to examine the underlying neural processes of spatial and non-spatial filtering costs more thoroughly and to examine how suppression is applied to overcome these interference effects. The triple compound version of our task will be used in Experiments 3 and 4 as IEMs may be biased if trained on trials with a unique conjunction (red diamond) as used in Experiment 1. Disentangling the salient distractor (color singleton) from targets and less salient nontargets as used in the triple compound task in Experiment 2 should allow for an unbiased IEM.

Method Experiment 3 & 4

Participants

Twenty-five volunteers naive to the paradigm and objectives of the study participated for payment (~$15 per hour) in each experiment. In Experiment 3, participants were aged 18-31 years (M = 22.8, SD = 4.0), nine participants were female, and five were left-handed. In Experiment 3, participants were aged 18-31 years (M = 22.8, SD = 4.0), nine participants were female, and five were left-handed. In Experiment 4, participants were aged 18-33 years (M = 22.2, SD = 3.7), sixteen participants were female, and one was left-handed. All participants were tested for normal or corrected-to-normal visual acuity and normal color vision. Both experiments were conducted with the written understanding and consent of each participant. The University of Chicago Institutional Review Board approved experimental procedures.

Apparatus, stimuli, and procedure

Apparatus and stimuli were identical to Experiment 2 with the following exceptions. Participants were seated with a chin-rest to allow for tracking gaze position. While in Experiment 3, the distractor was always red (when present) the distractor had distinct colors for target versus

nontarget positions (see Fig. 1C). Distractor were red/green for nontarget locations and green/red for target locations (balanced across participants). In contrast to Experiment 1 and 2, each trial began with a preparation display that presented subjects with a black fixation dot in the center of the screen (0.25° diameter, RGB: 0-0-0). Participants were told to fixate the dot and not move their eyes or blink until the end of a trial. After subjects pressed the spacebar to start the trial, the trial procedure followed as described for Experiment 2. The duration of the fixation cross display varied randomly from 400-600 msec in 20 msec steps. The inter-trial interval varied randomly from 800-1200 msec in 50 msec steps.

The experiment consisted of 28 blocks of 72 trials (2016 trials in total). Half the trials (1008) were distractor-absent, the other half (1008) were distractor-present. Gaze position was tracked at a sampling rate of 1000 Hz for both eyes with an EyeLink 1000+ eye tracker (SR Research Ltd.). A direct gaze violation feedback procedure was applied from halfway through the fixation display until participants responsed or the response time window ended. The trial was aborted if the participants' gaze was not within 1.5° of the center of the fixation cross during this time or if they blinked. A message (either "Eye movement" or "Blink") was presented on the screen, and then the next trial began with the new preparation display. Each aborted trial was added back into the sequence of upcoming trials, extending the experiment by one trial, and the trial sequence was re-shuffled so as to make the aborted trial's reappearance unpredictable. The mean number of total trials (including repeated trials) was 2140 (SD = 126) in Experiment 3 and 2224 (SD = 171) in Experiment 4.

Design

With regards to behavioral measures, the same conditions were used in Experiment 3 and 4 as in Experiments 1 and 2. With regards to event-related potentials (ERPs), the lateralization of stimuli plays a crucial role (Hickey et al., 2009; Woodman & Luck, 2003). For ERP analyses, we focused on trials in which either the target was presented laterally and the distractor was on the vertical midline (or absent) or the distractor was presented laterally and the target was on the vertical midline. These trials do not confound target and distractor activity in the lateralized ERP and allow to disentangle

target and distractor processing. The ERP was analyzed separately for target- distractor distances 0, 1, or 2. This resulted in seven conditions for ERP analyses in both Experiment 2 and 3: (i) Target lateral, singleton absent; (ii) Target and singleton at same lateral location, distance 0; (iii) Target lateral, singleton midline, distance 1; (iv) Target lateral, singleton midline, distance 2; (v) Singleton lateral, target midline, distance 1; (vi) Singleton lateral, target midline, distance 2.

EEG Recording

EEG was recorded using Ag-AgCl active electrodes (Brain-Products actiCAP) from 32 scalp sites (according to the International 10/20 System: FP 1/2, F7/8, F3/4, Fz, FC5/6, FC1/2, C3/4, Cz, TP9/10, CP5/6, CP1/2, P7/8, P3/4, PO7/8, PO3/4, Pz, O1/2, Oz). FPz served as the ground electrode and all electrodes were referenced online to TP10 and re-referenced off-line to the average of all electrodes. Incoming data were filtered [low cut-off = .01 Hz, high cut-off = 250 Hz, slope from low- to high-cutoff = 12 dB/octave] and recorded with a 1000 Hz sampling rate. Impedances were kept below 10 kΩ. Horizontal and vertical electrooculograms (EOGs) were recorded with passive electrodes bipolarly of approximately 1 cm from the outer canthi of the eyes and from 1 cm above and 2 cm below the observers' right eye, respectively.

Data Analysis

Behavioral data analyses were identical to Experiment 1 and 2. EEG was averaged off-line over a 700-ms epoch including a 200-ms pre-stimulus baseline with epochs time-locked to search display onset. Trials with incorrect or no responses were excluded. Trials with eye-related artifacts from -200 to 600 ms were excluded from the analysis (Experiment 2: M = 18.0%, SD = 11.3%; Experiment 3: M = 23.8%, SD = 12.8%). To identify eye-related artifacts, eye tracking data was first baselined identically to EEG data (i.e., subtraction of the mean amplitude of x and y coordinates for the time from -200 – 0 ms). Then, the Euclidian distance from the fixation cross was calculated from baselined data. We identified saccades with a step criterion of 0.5° (comparing the mean position in the first half of a 50-ms window with the mean position in the second half of a 50-ms window; window moved in 20-ms steps). We identified drifts by eye tracking data indicating a distance from the fixation > 1.2°. To

minimize false alarms due to noise in the data, both eyes had to indicate an eye-related artifact for a trial to be excluded from analysis. For one participant, eye tracking data of sufficient quality was not available. For this participant, the same procedure as for eye tracking based artifact rejection was used with these criteria: 25 µV hEOG (difference left and right channel), 100 µV for vEOG (difference upper and lower channel). Participants with fewer than 1000 trials were excluded from analyses (Experiment 3: n = 1; Experiment 4: n = 2). For all ERP-relevant conditions (see above), mean contralateral and ipsilateral ERP activity was calculated for each participant for an electrode pool of the three symmetric sites PO7/PO8, P7/8, PO3/4. For statistical analyses, the lateralized waveform (contra- minus ipsilateral activity) was used. The time windows for statistical analyses were determined in a data-driven way. For each component of interest, a 100-ms time window was determined around the peak of the component collapsed across conditions. The mean amplitude of the respective component was calculated for these time windows and forwarded to ANOVAs for repeated measures. The N2pc was compared for trials with lateral targets and no distractor, distractors at distance 1 and distractors at distance 2. The Ppc, distractor-N2pc, and Pd were compared for trials with lateral distractors and targets in the same position as the distractor, for targets at distance 1, and for targets at distance 2.

Inverted encoding model

While ERPs allow the measurement of visual priority on the coarse scale of left versus right hemifield, inverted encoding models can be used to reconstruct spatially selective channel tuning functions from the topographic distribution of EEG activity across electrodes (Ester et al., 2015; Fahrenfort et al., 2016; Foster et al., 2016). We used an IEM that assumes that power measured at each electrode reflects the weighted sum of six spatial channels (representing neuronal populations), each tuned for one of the six item positions. The IEM was run on evoked power (activity phase-locked to stimulus onset). To isolate frequency-specific activity, raw EEG segments were band-pass filtered for the alpha frequency range (8-12 Hz) using a two-way least-squares finite-impulse-response filter (‘‘eegfilt.m’’ from EEGLAB Toolbox) and then hilbert-transformed. The complex analytic signal was first averaged across trials, and then the complex magnitude of the averaged analytic signal was

squared. In a training stage, segmented, filtered waveforms from distractor-absent trials (equaled for target location) were used to estimate the weights for a model of the target's spatial position in a least-squares estimation. Each artifact-free trials were assigned to one if two bins (block assignment had 1000 iterations to allow for cross-validation). In the test stage, the model was inverted to transform the remaining half of trials (equaled for positions) into estimated channel responses, using the previously determined weights, for each of the two blocks. Channel responses were averaged across blocks and block assignment iterations. Testing was done twice using the same trials; once using the target position labels, once using the distractor position labels. This means that a common set of training data was used to estimate the channel responses for targets and singletons separately, but in the same trials. This procedure precludes the possibility that any observed effects of attention deployment are due to differences that arose during training or because of using distinct "basis sets" for the two conditions. The six channel response functions were shifted to a common center and averaged to obtain the CTF. The slope of the CTFs (estimated by linear regression computed for each time point) was used as a metric to compare attention deployment towards target and distractor. The slope was compared between channels tested on target versus distractor position with t-test for dependent measures for each time point between 0 and 500 ms. Only clusters of significance in which 50 consecutive data points (i.e., 50 ms) have to show a $p < .05$ were considered reliable.

Results Experiment 3 and 4

Behavioral results Experiment 3. Response times (RT) varied as a function of Distractor location, $F(2,46) = 33.7$, $p < .001$, $\eta^2 = .59$ (see Fig. 3, upper middle panel). Follow-up t-tests for dependent measures indicated that RTs were faster for distractor absent trials (M = 558 ms) than for Dist=0 trials (M = 583 ms), $t(22) = 5.2$, $p < .001$, and faster than for Dist>0 (M = 609 ms), $t(22) = 11.9$, $p < .001$. Further, RTs were faster for Dist=0 than for Dist>0, $t(22) = 2.9$, $p = .004$. Accuracy varied as a function of Distractor location, $F(2,46) = 15.1$, $p < .001$, $\eta^2 = .40$. Follow-up t-tests for depended measures indicated that accuracy was higher for distractor absent trials (M = 92.2 %) than for Dist=0

(M = 91.1 %), t(23) = 3.0, p = .007, and higher than for Dist>0 (M = 88.9%), t(23) = 6.8, p < .001. Further, accuracy was marginally higher for Dist=0 trials than for Dist>0 trials, t(23) = 1.9, p = .073.

A one-way ANOVA for repeated measures (factor levels distance 0, 1, 2, and 3) showed that RTs varied as a function of distance between target and distractor, F(3,69) = 13.4, p < .001, η^2 = .37 (see Fig. 3). All pairwise comparisons were significant (all p ≤ .037) except the comparison between distance 0 and 3 (p = .237). Similar results were obtained for accuracy: accuracy varied as a function of distance between target and distractor (M_0 = 91.1 %, M_1 = 87.2 %, M_2 = 89.7 %, M_3 = 90.4 %), F(3,69) = 11.8, p < .001, η^2 = .34. Pairwise comparisons were significant (all p < .001) except for distance 0 versus 3, 0 versus 2, and 2 versus 3 (p ≥ .067). In summary, error rates showed the same descriptive pattern as RT and replicates most differences statistically, ruling out a speed-accuracy tradeoff.

In compatible trials (target and distractor line of same orientation) RTs were shorter (M = 596 ms) than in incompatible trials, (M = 622 ms), t(23) = 8.3, p < .001, d = 0.48. Analogously, accuracy was higher in compatible trials (M = 91.7%) than in incompatible (M = 86.1%) trials, t(23) = 5.2, p < .001, d = 0.77

Behavioral results Experiment 4. Response times (RT) varied as a function of Distractor location, F(2,44) = 41.9, p < .001, η^2 = .66 (see Fig. 3). Follow-up t-tests for depended measures indicated that RTs were faster for distractor absent trials (M = 585 ms) than for Dist=0 (M = 609 ms), t(23) = 5.7, p < .001, d = 0.41, and faster than for Dist>0 trials (M = 622 ms), t(23) = 9.7, p < .001, d = 0.65. Further, RTs were faster for Dist=0 than for Dist>0 trials, t(22) = 3.1, p = .005, d = 0.23. Similarly, accuracy varied as a function of Distractor location, F(2,44) = 9.1, p = .001, η^2 = .29. Follow-up t-tests for dependent measures indicated that accuracy was higher for distractor absent trials (M = 92.7%) than for Dist=0 trials (M = 91.5%), t(22) = 2.5, p = .021, d = 0.24, and higher than for Dist>0 trials (M = 90.3%), t(22) = 4.2, p < .001, d = 0.47. Further, accuracy was marginally higher for Dist=0 than for Dist>0 trials, t(22) = 1.9, p = .068, d = 0.23.

A one-way ANOVA for repeated measures showed that RTs varied as a function of distance between target and distractor, F(3,66) = 25.7, p < .001, η^2 = .54 (see Fig. 3). All pairwise comparisons

were significant (all $p \leq .002$) except for the comparison distance 0 versus 3 and 0 versus 2 (both $p \geq .116$). Similarly, accuracy varied as a function of distance between target and distractor ($M_0 = 91.5$ %, $M_1 = 89.1$ %, $M_2 = 91.0$ %, $M_3 = 91.6$ %), $F(3,66) = 6.1$, $p = .004$, $\eta^2 = .22$. Pairwise comparisons were significant (all $p \leq .005$) except for distance 0 versus 2, 0 versus 3, and 2 versus 3 (all $p \geq .285$). In summary, error rates showed the same descriptive pattern as RT and replicates most differences statistically, ruling out a speed-accuracy tradeoff.

In compatible trials RTs were shorter (M = 615 ms) than in incompatible trials (M = 629 ms), $t(22) = 5.5$, $p < .001$, $d = 0.25$. Similarly, accuracy was higher (M = 92.3%) in compatible than in incompatible trials (M = 88.4%), $t(22) = 6.1$, $p < .001$, $d = 0.68$.

Comparison Experiment 3 and 4. Behavioral results of Experiment 3 and 4 were virtually identical. This was first confirmed with a ANOVA for repeated measures using the within-subjects factor Trial type (distractor-absent, dist=0, dist>0) and the between-subjects factor Experiment (3 versus 4), which showed neither a main effect of Experiment, $F(1,45) = 2.0$, $p = .162$, $\eta^2 = .04$, nor an interaction of Trial type and Experiment, $F(2,90) = 1.9$, $p = .163$, $\eta^2 = .04$. Second, an ANOVA for repeated measures was run using the within-subjects factor Distance (0, 1, 2, 3) and the between-subjects factor Experiment (3 versus 4). Neither Experiment, $F(1,45) = 1.1$, $p = .303$, $\eta^2 = .02$ nor the interaction of Experiment and Distance, $F(3,135) = 1.2$, $p = .293$, $\eta^2 = .03$ showed reliable effects. Thus our results indicate that using a distinct color for distance-zero trials where targets and distractors coincide does not yield an attention deployment different from using the same color for distance-zero and other distance > 0 trials. We thus collapsed the EEG data from Experiments 3 and 4 to achieve a higher statistical power.

ERP results Experiment 3 and 4.

N2pc in target-lateral trials. The target-N2pc time window was determined as 223-322 ms. Target-N2pc amplitude varied as a function of distractor condition, $F(2,92) = 7.0$, $p = .001$, $\eta 2 = .13$. Follow-up t-tests for dependent measures showed that the N2pc was larger in distractor-absent trials (M = -0.93) than for distractors at distance 1 (M = -0.56), $t(46) = 3.2$, $p = .002$, $d = 0.51$, but not

larger than for distractors at distance 2 (M = -0.85), t(46) = 1.0, p = .327, d = 0.11. N2pc amplitude was larger for distractors at distance 2 than at distance 1, t(46) = 2.6, p = .012, d = 0.39. The N2pc was significantly different from zero in all conditions (all p < .001).

N2pc in distractor-lateral trials. The N2pc time window for distractor lateral trials was determined as 175-274 ms. N2pc amplitude in trials with lateral distractors varied as a function of target distance, F(2,92) = 26.7, p < .001, η2 = .37. Follow-up t-tests for dependent measures showed that the N2pc elicited by coinciding distractor and target (M = -1.43) was larger than the distractor-N2pc for targets at distance 1 (M = -0.69), t(46) = 6.2, p < .001, d = 0.68, and for targets at distance 2 (M = -0.85), t(46) = 5.6, p < .001, d = 0.49. Distractor-N2pc amplitude was equally large for targets at distance 2 and at distance 1, t(46) = 1.7, p = .095, d = 0.16. The N2pc was significantly different from zero in all conditions (all p < .001). In addition, the N2pc was larger in trials with coinciding target and distractor than in distractor absent trials, t(46) = 4.1, p < .001, d = 0.47.

Distractor positivity (Pd). The Pd time window was determined as 255-354 ms. Pd amplitude in trials with lateral distractors varied as a function of target distance, F(2,92) = 48.0, p < .001, η2 = .51. Follow-up t-tests for dependent measures showed that the Pd elicited by coinciding distractor and target (M = -0.20) was smaller than the Pd for targets at distance 1 (M = 1.24), t(46) = 8.7, p < .001, d = 1.18, and for targets at distance 2 (M = 0.82), t(46) = 6.2, p < .001, d = 0.92. Pd amplitude was larger for targets at distance 1 than at distance 2, t(46) = 3.6, p = .001, d = 0.44. The Pd was significantly different from zero for distance 1 and 2 (both p < .001), but not for coinciding target and distractor (p = .310).

Exploratory analysis: Posterior positivity contralateral (Ppc). The Ppc time window was determined as 79-178 ms. Ppc amplitude did not vary as a function of distractor condition, F(2,92) = 2.2, p = .121, η2 = .05. The Ppc was significantly different from zero in all conditions (all p < .001).

Exploratory analysis: Contralateral Delay Activity (CDA). Visual inspection of the lateralized ERP waveforms showed that after typical analysis time windows of attentional components, a sustained negativity was found. A one-way ANOVA using each of the six conditions as a factor level

indicated that CDA varied between conditions, $F(5,230) = 13.7$, $p < .001$, $\eta 2 = .23$. Follow-up t-tests for dependent measures showed that the CDA elicited in trials with coinciding target and distractor was larger than in any other condition (all $p < .001$), whereas the CDA did not vary among any other conditions (all $p \geq .169$), all two-tailed.

IEM results Experiment 3 and 4

Similar to ERP analyses, we collapsed the EEG data from Experiments 3 and 4 to achieve a higher statistical power. The channel tuning functions (CTFs) are shown in Fig. 5. As a measure of spatial selectivity, the slope for the channel tuning functions was calculated for both the target location (blue lines) and the distractor location (red lines). The IEM run on alpha bandpass (8-12 Hz) filtered data shows a slope reliably different from zero from 17-500 ms (targets) and 33-289 ms (distractors). The distractor slope was reliably steeper than the target slope from 156-227 ms. The target slope was reliably steeper than the distractor slope from 328-500 ms. This shows that the channels were first selective for both target and distractor position, but more so for distractor position. Then, channels continued to be selective for the target position and not for the distractor position anymore. The IEM run on theta bandpass (4-8 Hz) filtered data shows a slope reliably different from zero from 5-500 ms (targets) and 262-312 ms (distractors). The target slope was reliably different from the distractor slope from 137-500 ms. This shows that the channels were selective for both target and distractor position, but in a negative manner for distractors. Channels optimized to represent attentional enhancement of the target showed below baseline activity when a distractor was presented at the position they were tuned to.

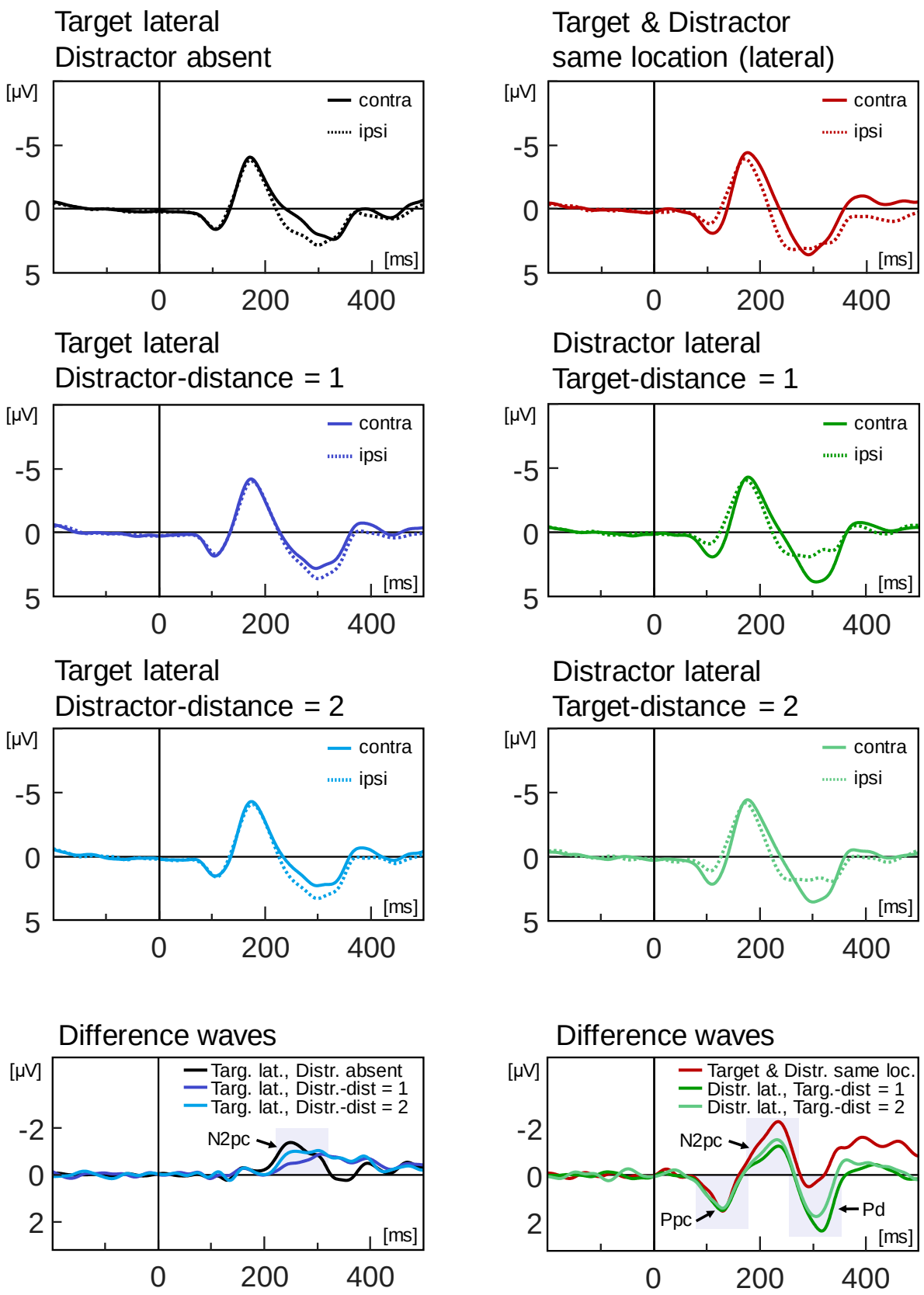

Figure 4. Grand average event-related potentials collapsed across Experiment 3 and 4. The upper left column shows trials in which the target was presented laterally and the distractor was presented on the vertical midline. The right panels show trials in which the distractor was presented laterally and the target was presented on the vertical midline (or target was at distractor location, red lines). The lowest row shows the difference waves (contra minus ipsilateral) for the same conditions as shown in the upper rows. Signal is pooled across PO7/8, P7/8 and PO3/4. For display purposes, signal was filtered with a 30Hz lowpass filter. All statistical analyses were conducted on unfiltered data. Grey shaded areas show the time windows used for statistical purposes.

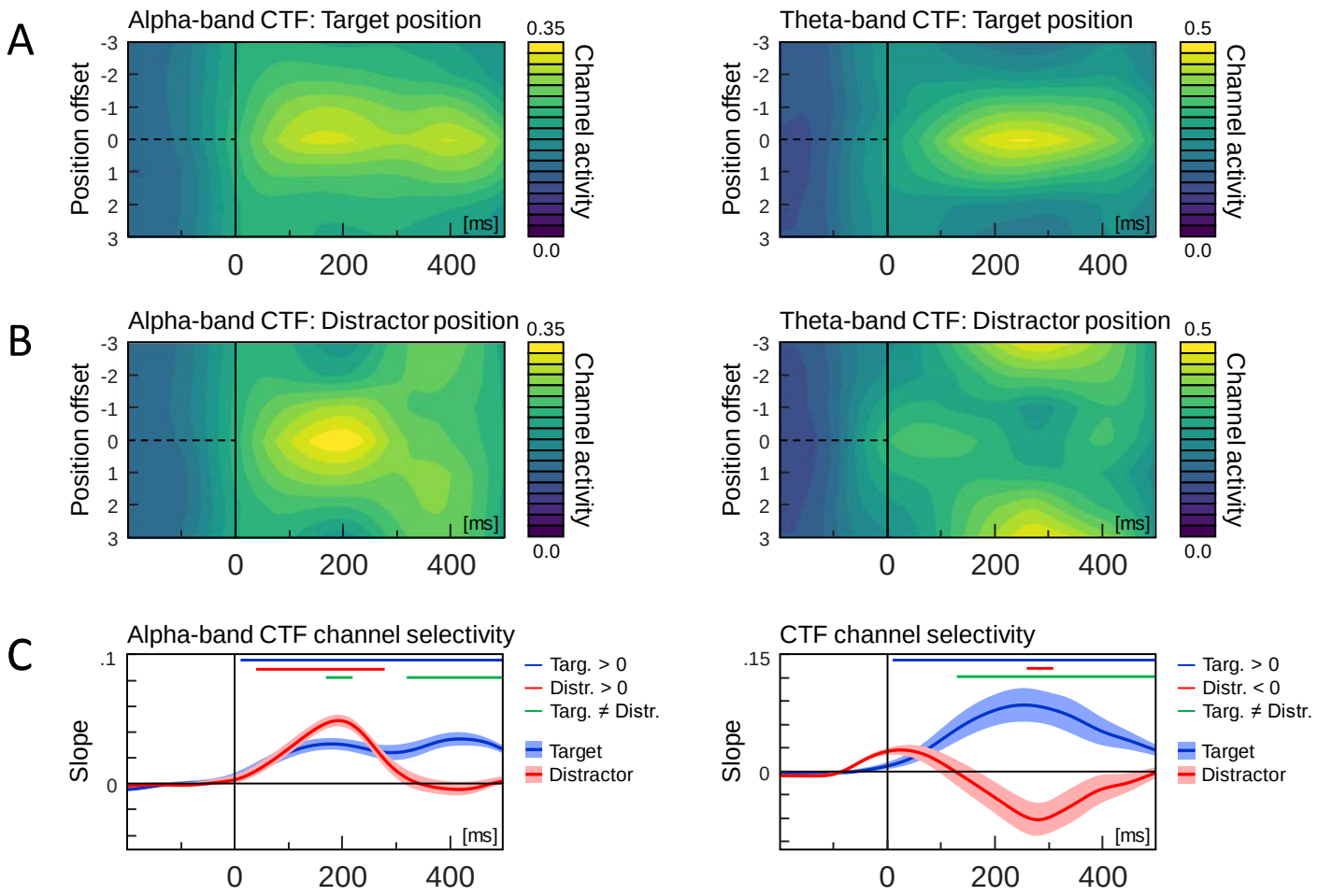

Figure 5. Channel tuning functions for evoked alpha-band (8-12 Hz) activity (left panels) and evoked theta-band (4-8 Hz) activity (right panels). All CTFs are trained on target position in distractor-absent trials and tested on (A) target position and (B) distractor positions in distractor-present trials. The slope of the CTFs in (A) and (B) is show in (C) as blue lines (target) and red lines (distractor). Thin blue lines show time point where the target-CTF slope is different from zero, thin red lines show where the distractor-CTF is different from zero. Thin green lines show where target-CTF and distractor-CTF differ from one another. Only time points in clusters of at least 50 subsequent time points (= 50 ms) with $p < .05$ are highlighted. Shades indicate standard errors of the mean, corrected for individual differences (Cousineau, 2005).

Intermediate discussion

General Discussion

This study presents a comprehensive analysis of the spatial deployment of attention when conflicting information is presented to the visual system. We used converging evidence from behavioral and EEG data to track the time course of two subprocesses of visual selective attention: attentional enhancement and attentional suppression. First, we replicate the well-established additional singleton effect: Response times (RTs) were longer when a color singleton, serving as a distractor, was presented simultaneously to a shape target (Theeuwes, 1992, 2010). Second, we replicate earlier findings showing that these RT costs for distractor-present trials decreased with distance between target and distractor (e.g., Gaspar & Mcdonald, 2014). The exception were trials in which the distance was zero, i.e., target and distractor were presented in the same position. In these distance-zero trials, RTs were shorter than for any other distance, but longer than for distractor-absent trials.

Distractor interference and distance effects were reflected in the neural markers of attention as well. Distractors elicited an N2pc, followed by a distractor positivity (Pd), suggesting they captured attention and were then suppressed. The Pd component was larger for distractors adjacent to a target than for distractors further away. This suggests that the amount of suppression applied to distractors varied as a function of target-distractor distance. The distractor-N2pc, however, did not vary as a function of target-distractor distance, suggesting that distractors near a target captured attention equally strongly as distractors further away from a target. The target-N2pc was larger when target and distractor were further away, suggesting that attentional enhancement of relevant information may be impaired when a distractor is in close proximity. When target and distractor coincided, however, no Pd was observed and instead a large N2pc was found, suggesting that target-distractor compounds were particularly strongly attended.

The IEM allowed us to use the spatial selectivity of channels tuned to all possible locations to track attentional enhancement and suppression in a time-resolved manner. Alpha-band (8-12 Hz) activity showed that initially, both targets and distractors were attended, but distractors more so than

targets. From ~280 ms on, only targets were attended. Theta-band (4-8 Hz) activity also tracked attention deployment towards the target, but importantly, showed below-baseline spatial selectivity for the distractor, most pronounced at ~290 ms. This may be indicative of distractor suppression, applied to irrelevant information in order to overcome distraction and facilitate target enhancement.

Distractors induce interference

We found RT costs, i.e., longer RTs for distractor-present compared to distractor-absent trials in all four experiments. This is in line with a large body of studies that showed the presence of salient irrelevant stimuli can interfere with processing less salient, but relevant stimuli (Theeuwes, 1992, 2010; see also Burra & Kerzel, 2014; Feldmann-Wüstefeld et al., 2015; Liesefeld et al., 2017; Sawaki & Luck, 2013). Several studies found that distractors only cause interference when they share features with the target or resemble relevant stimuli (Folk et al., 1992; Folk & Remington, 2006) while others found that distractors only cause interference when participants are in singleton detection mode, i.e., they search for any discontinuity in the visual field (Bacon & Egeth, 1994; Lamy & Egeth, 2003; Leber & Egeth, 2006). In the present study, the target was always a diamond shape which should induce feature search mode (i.e., the search for a predefined, distinct feature) rather than singleton detection mode in which physically salient items general tend to drag attention (Bacon & Egeth, 1994). Furthermore, target and distractor were distinct in shape and color which should prevent contingent capture (Folk & Remington, 1998). Nevertheless, the RT costs we found demonstrate strong distractor interference throughout all experiments. Are there reasons to assume the distractor did not capture attention automatically, but rather that attending the distractor was top-down guided or to some extent deliberate? It could be argued that in Experiment 1, participants may have searched for red items in anticipation the target would be red in a sufficiently high ratio of trials. Alternatively they may have used any red item as an convenient starting point of their search (Becker, 2007). As the target was red in only 1/12 of the trials, this seems like an bad strategy, though. Furthermore, the RT costs we observed in trials in which the target was red (compared to trials without color singleton), speak

against a deliberate attention deployment towards the distractor. In Experiments 2 & 3, targets were never colored but could appear in the same location as the colored distractor (again, in 1/12 of the trials). As participants were instructed to search for the red diamond and the diamond itself was never red, this should render the strategy search for red items even less efficient than in Experiment 1. In Experiment 4, distractors had a different color when presented at the same location as targets. This should both render the target-associated color more relevant and the distractor-associated color less relevant and thus make top-down guided attention deployment towards distractors unlikely. Consequently, the distractor-induced interference observed in all experiments was likely due to involuntary attentional capture.

Our neural data supports the notion of attentional capture. Distractors elicited an N2pc, indicative of attention deployment, in all conditions. This is in line with previous studies who found that salient distractors elicited an N2pc (Feldmann-Wüstefeld et al., 2015, 2016; Hickey et al., 2009; Hilimire & Corballis, 2014; Kiss et al., 2012; Liesefeld et al., 2017; Sawaki & Luck, 2013). Analogously to the distractor-N2pc, the topography of alpha-band (8-12 Hz) activity tracked attention deployment towards the distractor early on (peaking at ~190 ms), and more strongly than the target. Attention deployment towards the distractor was transient (ending at ~280 ms). This further supports the notion of automatic and fast attentional guidance by the most salient item (Belopolsky et al., 2010; Liesefeld et al., 2017; Theeuwes et al., 2000).

Unsurprisingly, an N2pc was also elicited by the targets, suggesting targets were attended. Alpha band activity accompanied the N2pc and tracked attention deployment towards the target in a sustained fashion, even after distractor processing discontinued, in line with the idea that attention can be strongly guided by top-down attention deployment. One mechanism that may have supported eventual attention deployment towards the target was active suppression of the distractor, as evident in the Pd component that distractors consistently elicited. The Pd has been shown to track suppression below baseline to facilitate processing of relevant information (Burra & Kerzel, 2014; Feldmann-Wüstefeld et al., 2020; Gaspar & Mcdonald, 2014; Gaspelin & Luck, 2018; Liesefeld et al., 2017). Some

studies found no distractor-N2pc in trials in which a Pd component indicated distractor suppression (Burra & Kerzel, 2014; Feldmann-Wüstefeld et al., 2020; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018; Jannati et al., 2013). It is conceivable that the presence of both distractor-N2pc and Pd indicate that a salient item first captures attention before it is suppressed (Liesefeld et al., 2017). Thus in the present study, participants may have applied suppression to distractors to overcome the attentional capture observed in the beginning of a trial. A negative slope in the theta band (4-8 Hz) channel activity of the IEM tracked the location of the distractor and suggests that the suppression was maximal at ~280 ms.

Neural ambiguity increases with proximity of target and distractor – spatial effects of attentional suppression and enhancement

Attentional capture by and suppression of distractors varied as a function of the distance between target and distractor, replicating earlier studies (Caputo & Guerra, 1998; Gaspar & McDonald, 2014; Hickey & Theeuwes, 2011; Koch et al., 2013; Kwak et al., 1991; Mounts, 2000; Starreveld et al., 2004; Theeuwes et al., 2004). In all four experiments, RTs costs induced by distractors increased with proximity to the target location, suggesting interference is stronger when conflicting stimuli are close to one another, in line with the neural ambiguity account (Desimone & Duncan, 1995; Hickey & Theeuwes, 2011; Luck, Girelli, et al., 1997; Mounts, 2000). The neural ambiguity account posits that suppression of the singleton and enhancement of the target are in direct opposition; the closer target and singleton are, the more do receptive fields of neurons representing these items overlap and this impairs the filtering process necessary to extract relevant information. This spatial gradient of interference together with the same location benefit (faster RTs for coinciding target and distractor than for target and distractor in different positions) and compatibility effects (slower RTs when target and distractor identity differed) emphasize the spatial component of filtering.

Event-related potentials offer a possible explanation of the gradient of interference observed in the behavioral data. Both the Pd as a measure of distractor suppression and the N2pc as a measure

of target enhancement were affected by target-distractor distance – but in an inverse fashion. Pd amplitude was found to be larger for singletons adjacent to the target compared to singletons at distance 2 *(note that a distance of three could not be analyzed as for singletons on the midline, a distance of three would indicate that the target was on the vertical midline as well, making it impossible to analyze lateralized potentials)*. This is in line with the neural ambiguity account that posits items in the vicinity of an attended object need more suppression (Luck, Girelli, et al., 1997). At the same time, the N2pc amplitude was smaller for targets when a distractor was nearby. Thus, the visual systems seems to resolve the neural ambiguity by applying more suppression to distractors near the target at the cost of enhancing the target itself. As a result, attentional enhancement of the target is less efficient when a distractor is nearby as resources are dedicated to suppressing a nearby singleton. The N2pc was argued to reflect filtering out of irrelevant information or shielding relevant information from interference by irrelevant information (Hickey et al., 2009; Luck, Chelazzi, et al., 1997; Luck, Girelli, et al., 1997). For example, the closer a distractor is presented to the target, the larger the target-N2pc (Luck, Girelli, et al., 1997). Our results are at odds with this notion but in line with the previous finding (Gaspar & McDonald, 2014) that the N2pc decreases with increasing proximity of distracting information. Our findings support an opposing view of the N2pc, namely that it merely reflects attentional enhancement, or localization/identification of relevant information (Eimer, 1996; Feldmann-Wüstefeld et al., 2013; Mazza et al., 2007). It was previously suggested that increased RT costs for distractors near targets are due to more attentional capture (Hickey & Theeuwes, 2011; Mounts, 2000). However, as the N2pc elicited by the distractor did not vary as a function of distance, this seems like a less likely explanation. In fact, the finding that the N2pc amplitude for distractors was not affected by target-distractor distance suggests that the longer RTs in trials in which distractors were presented close to the target were due to nonspatial interference (see below) or spatial suppression (distance-dependent Pd component). The Ppc that was associated with early suppression (Barras & Kerzel, 2017; Feldmann-Wüstefeld & Vogel, 2019; Weaver, van Zoest, et al., 2017) was not affected by target-distractor distance. This may be because the Ppc reflects an early “attend-to-me”

signal (Sawaki & Luck, 2010) signal that is not modulated by the amount of interference but rather reflects activity on the priority/salience map (Barras & Kerzel, 2017). In this context the Pd can be seen as a response to that signal that reflects more (close targets) or less (further away targets) effortful suppression of the initial signal on the priority/salience map.

The gradient of top-down target enhancement and bottom-up distractor enhancement were also reflected in the alpha-band topography. Channel selectivity was highest for targets presented in the location a channel was tuned for and then gradually dropped for more distant locations, replicating earlier studies (Foster, Sutterer, Serences, Vogel, & Awh, 2017; Feldmann-Wüstefeld & Awh, 2020). Here, we replicate a gradual tuning profile for distractors, too, suggesting that attentional capture by distractors can be tracked in a time-resolved fashion as well. Moreover, we show that theta and alpha are picking up on qualitatively different aspects of attentional processing. While channels trained on alpha-band activity induced by targets show a high activity when both tested on target and distractor location (albeit with different time courses), channels trained on theta-band (4-8 Hz) activity induced by targets show a particularly low activity when tested on distractor position, hinting at the possibility that attentional suppression can be tracked with theta-band topographies. Similar to the alpha-band activity, theta-band activity shows a graded tuning profile, i.e., channels show lowest activity when the distractor is presented at the location they are tuned for, and then gradually rise towards more distant locations. These results suggest a gradual deployment of suppression throughout the visual field.

Nonspatial filtering costs

Same location benefits, distance-dependent RTs, compatibility effects, as well as distance-dependent Pd and target-N2pc amplitudes provide converging evidence of spatial filtering costs. At the same time, distractor-N2pc amplitudes were distance-invariant, demonstrating that distractors did not capture attention more when they were near targets. On the contrary, when distractor and target coincided, the N2pc was larger than for distractors or targets presented alone. This suggests

attention deployment was most pronounced when target and distractor were presented in the same location, in line with the idea that locations where two singletons are presented (Krummenacher et al., 2002) or where both bottom-up and top-down fall in line (Fecteau & Munoz, 2006; Itti & Koch, 2000; Wolfe, 2007) should receive the highest activation on a priority map of attention. Interestingly, this did not result in the overall best performance, though; performance was better in distractor-absent than in distance-zero trials. The pure attentional capture account (Theeuwes, 1992, 2010) would predict that spatially coinciding target and distractor attract attention most strongly and thus produce shortest RTs. This distractor interference for distance-zero trials suggest non-spatial filtering costs were induced by distractors, on top of spatial filtering costs. This is in line with previous studies demonstrating that salient distractors induce nonspatial filtering costs (Becker, 2007; Folk & Remington, 1998; Folk & Remington, 2006; Wykowska & Schubö, 2011). Even though attention may have been steered more towards the target location when presented at the same location as the distractor, additional filtering was still necessary compared to the distractor-absent condition to extract the target features. Same location costs were also observed in contingent capture paradigms; longer RTs were found when a cue is presented in the same location as the subsequent target (Carmel & Lamy, 2014; Eimer, Kiss, Press, & Sauter, 2009; Lamy, Leber, & Egeth, 2004; Schoeberl, Ditye, & Ansorge, 2018). It was argued that object updating/integration of target and distractor over time (Carmel & Lamy, 2014) or inhibition of return (Belopolsky et al., 2010) can explain the same location costs in contingent capture paradigms. As in the present study, distractor and target were presented simultaneously, these seem unlikely to account for the same location costs we observed. Another explanation for same-location costs was that attending to the location of a to-be-suppressed item is delayed (Lamy et al., 2004). This was supported by the finding that the target-N2pc latency was longer when a target was preceded by an irrelevant cue (Eimer et al., 2009). In the distance-zero condition of the present study we did, however, not observe a Pd component that would have been indicative of suppression.

Nevertheless, the extraction of target features may have been delayed in the distance-zero condition due to nonspatial filtering costs. For example it was argued that the extraction of task-relevant features may be delayed when a target coincides with a salient task-irrelevant items because both items compete for attentional resources, even when presented in the same location (Folk & Remington, 2006; Kahneman et al., 1983; Treisman et al., 1983). Accordingly, in the present study, identifying the orientation of the line that was embedded in the target shape may have been impaired when a color singleton was presented in the same position because the color singleton draws resources. Accordingly, the large N2pc in distance-zero trials could be the neural signature of two items utilizing resources in the same position. Coinciding targets and distractors also elicited a stronger CDA than targets or distractors being presented in isolation. The CDA was originally found in a change detection task and related to maintaining information in working memory (Vogel et al., 2005; Vogel & Machizawa, 2004). The CDA was, however, later used to track sustained attention towards in-depth analyses of a selected visual item or the transition of attended information into working memory (Jolicœur et al., 2006; Kiss, Van Velzen, & Eimer, 2008; Mazza et al., 2007). In this context, the CDA we observed in the present study may be related to resolve the ambiguity at the target location when target and distractor compete for resources in the same location. Resolving this ambiguity, a process presumably rooted in working memory processes, may be the time-consuming process that resulted in the same location cost that we found behaviorally.

In sum the present study demonstrates both spatial and nonspatial filtering costs are induced by salient distractors in visual search for a less salient target. Our data do not allow to draw conclusions about the exact contribution to overall processing costs, but an approximation may be derived from comparing the difference between compatible and incompatible trials on one hand (indicative of spatial filtering) and the difference between distractor absent and distance-zero trials on the other hand (indicative of nonspatial filtering). Across four experiments, the compatibility effect was 18 ms on average whereas the same location cost was 23 ms on average. Interestingly, the sum matches exactly the overall RT costs (distractor-present minus distractor-absent) that were 41 ms. Thus, as a

first approximation, spatial and nonspatial interference may contribute 44% (18/41) and 56% (13/41), respectively, to overall processing costs induced by a salient distractor. Future research could attempt to measure the contribution of spatial and nonspatial interference to overall processing more directly.

The time course of attentional enhancement and suppression

In line with previous findings we show that distractors elicit a Ppc, then an N2pc followed by a Pd (Feldmann-Wüstefeld et al., 2016; Hilimire & Corballis, 2014; Kiss et al., 2012; Liesefeld et al., 2017; Sawaki & Luck, 2013). The Ppc, indicative of early suppression (Barras & Kerzel, 2017; Weaver, van Zoest, et al., 2017) was unaffected by target-distractor distance and peaked at 129 ms. The distractor-N2pc, indicative of attentional capture followed at 225 ms and the target-N2pc, indicative of deliberate attention deployment at 273 ms. Eventually, the Pd peaked at 305 ms. This is in line with the observation that attention is first captured by the most salient item, then both relevant and irrelevant items can be attentionally enhanced simultaneously while the suppression of the irrelevant items concludes the chain of attentional processes (Liesefeld et al., 2017).

Using alpha (8-12 Hz) and theta band (4-8 Hz) filtered EEG data in an inverted encoding model, we could track the subprocesses of attention in a time-resolved manner. The alpha-band topography showed a high selectivity for targets from early on that sustained throughout at least 500 ms, replicating earlier findings (Foster, Sutterer, Serences, Vogel, & Awh, 2017; Feldmann-Wüstefeld & Awh, in press). Alpha-band activity also showed an early selectivity for distractors from, that was initially more pronounced for the distractor than for the target in line with the early distractor-N2pc we observed and the notion that salient stimuli capture attention automatically and may receive priority over less salient, yet task-relevant items (Theeuwes, 2010). The spatial selectivity for distractor positions was transient, however and later exceeded by the spatial selectivity of targets, in line with the idea that attentional capture is followed by rapid disengagement (Belopolsky et al., 2010) as well as with the idea that top-down attention deployment eventually overrides attentional capture and thus allows to acquire task-relevant information (Leber & Egeth, 2006). Theta-band activity showed a

distinct and novel pattern when applied on distractor location: A negative (below-baseline) slope was found; thus theta-band CTFs were selective of distractor position but because of the negative slope, they may be the IEM equivalent of the Pd component. In support of that notion, the negative slope peaked at the approximately same time as the Pd. It is unclear, however, whether the theta-band activity is inherently representative of attentional suppression or merely reflects ERP oscillations; a visual inspection of the distractor lateral trials suggests an oscillation (Ppc, N2pc, Pd) of approximately 200 ms length which is tantamount to 5 Hz, i.e., well within the scope of the theta band (4-8 Hz). Regardless, using IEMs instead of the Pd to track suppression could be a very useful tool in the future because it allows a much more fine-grained analysis; while the Pd allows to differentiate between suppression in the left versus right hemifield, the IEM tracks at least six (as in the present study), possibly more locations, and it does so simultaneously. Also note we trained the model on target location and test it on either target or distractor location. By this means, we used the exact same trials in both models, physically equating displays (the 'Hillyard principle'; Luck, 2005) resulting in a model that tracks enhancement and suppression simultaneously and unbiased.

Conclusions

The present study used neural markers of attentional suppression and enhancement to investigate why salient distractors induce interference in visual search tasks. Distractors resulted in longer response times, showing that they induced interference. As distractors consistently elicited N2pc components, the interference is at least partially due to attentional capture at the distractor location. Spatial filtering costs are further supported by our findings that that the interference increases with spatial proximity between target and distractor. This increment was, however, not due to increased attentional capture by the distractor, but (i) increased need for suppression and (ii) decreased efficiency of target enhancement, in line with the neural ambiguity account. Inverted encoding models run on alpha-band (8-12 Hz) and theta (4-8 Hz) filtered EEG data revealed the time course of attention deployment: Alpha-band topographies were selective of target and distractor

enhancement and showed that both were initially attended, but the distractor more so. Later, only the target was attended. Theta-band topographies also tracked suppression of the distractor below baseline and showed that distractor suppression and target enhancement run in parallel. Importantly, when target and distractor coincided, response times were longer than in distractor-absent trials. This shows that distractor-induced interference costs are not just due to attentional capture, but also due to nonspatial filtering costs. We suggest that the interference costs induced by salient, irrelevant objects are due to a combination of spatial and nonspatial interference costs.

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